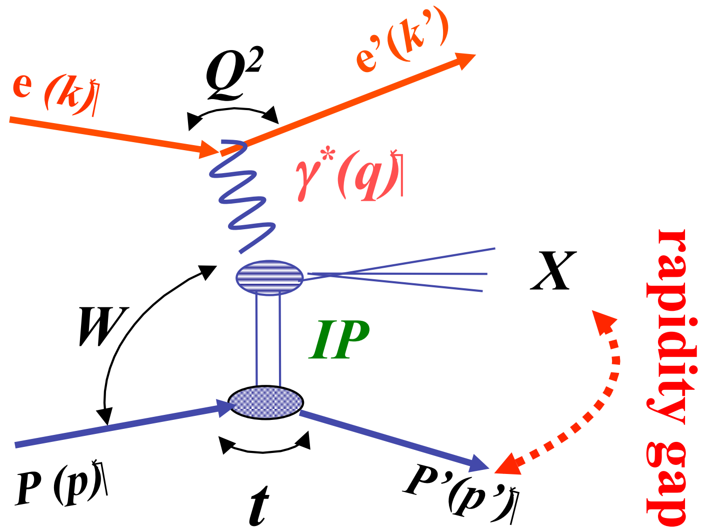
Exclusive diffraction from HERA to EIC/eRHIC

Salvatore Fazio
Brookhaven National Laboratory (Upton NY, USA)



Summer school on
Diffractive and Electromagnetic Processes at high energies
Acquafredda (Maratea, Italy), *Sep. 06 – 10, 2010*

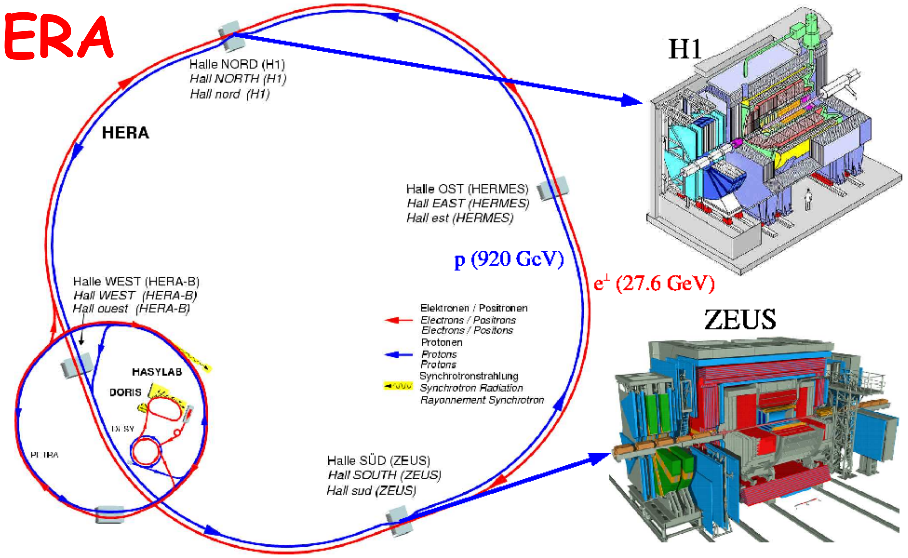
Planing of the talk

- Exclusive Diffraction
  - Real photon (DVCS) and Vector Meson Production
- The EIC/eRHIC project
  - t measurement with an eRHIC
- Pomeron in ep collisions
- A Regge-type description of the exclusive diffraction
- Summary

From HERA to an EIC collider

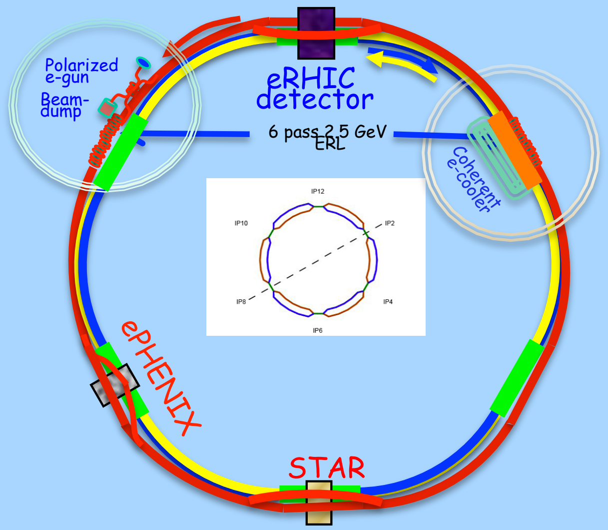
- 27.5 GeV electrons/positrons on 920 GeV protons $\rightarrow \sqrt{s}$=318 GeV
- 2 colliding experiments: **H1 and ZEUS**
- Total lumi collected at HERA: **500 pb^{-1}**, polarization of electrons/positrons at HERA II

HERA



Detectors not originally designed for forward physics, Roman pots added later

EIC/eRHIC



- **20 - 30 GeV electrons on 325 (125) GeV protons (nuclei). Polarization of electrons and protons (nuclei)**
- **Lumi: 1.4 x 10^{34} $cm^{-2}s^{-1}$**

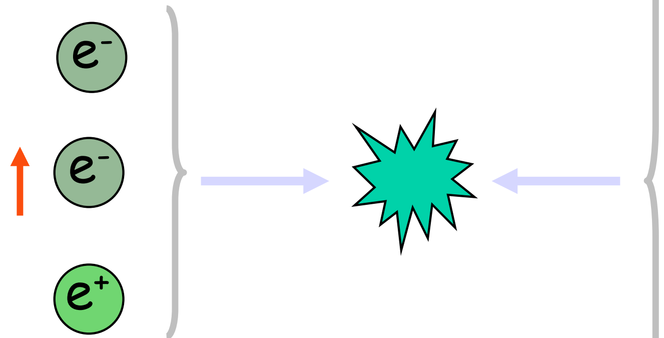
For exclusive diffraction the concept is similar to HERA but:

- **Dedicated forward instrumentation**
- **Higher tracker coverage**
- **Very High lumi!**

The eRHIC idea

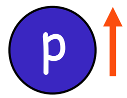
Electron accelerator
(to be build)

Unpolarized and
polarized leptons
4-20 (30) GeV

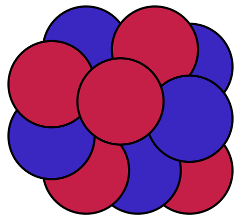


70% e^- beam polarization goal
polarized positrons?

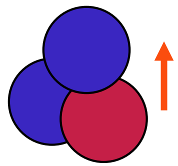
RHIC (Existing)



Polarized protons
50-250 (325) GeV



Heavy ions (Au,U)
50-100 (130) GeV/u

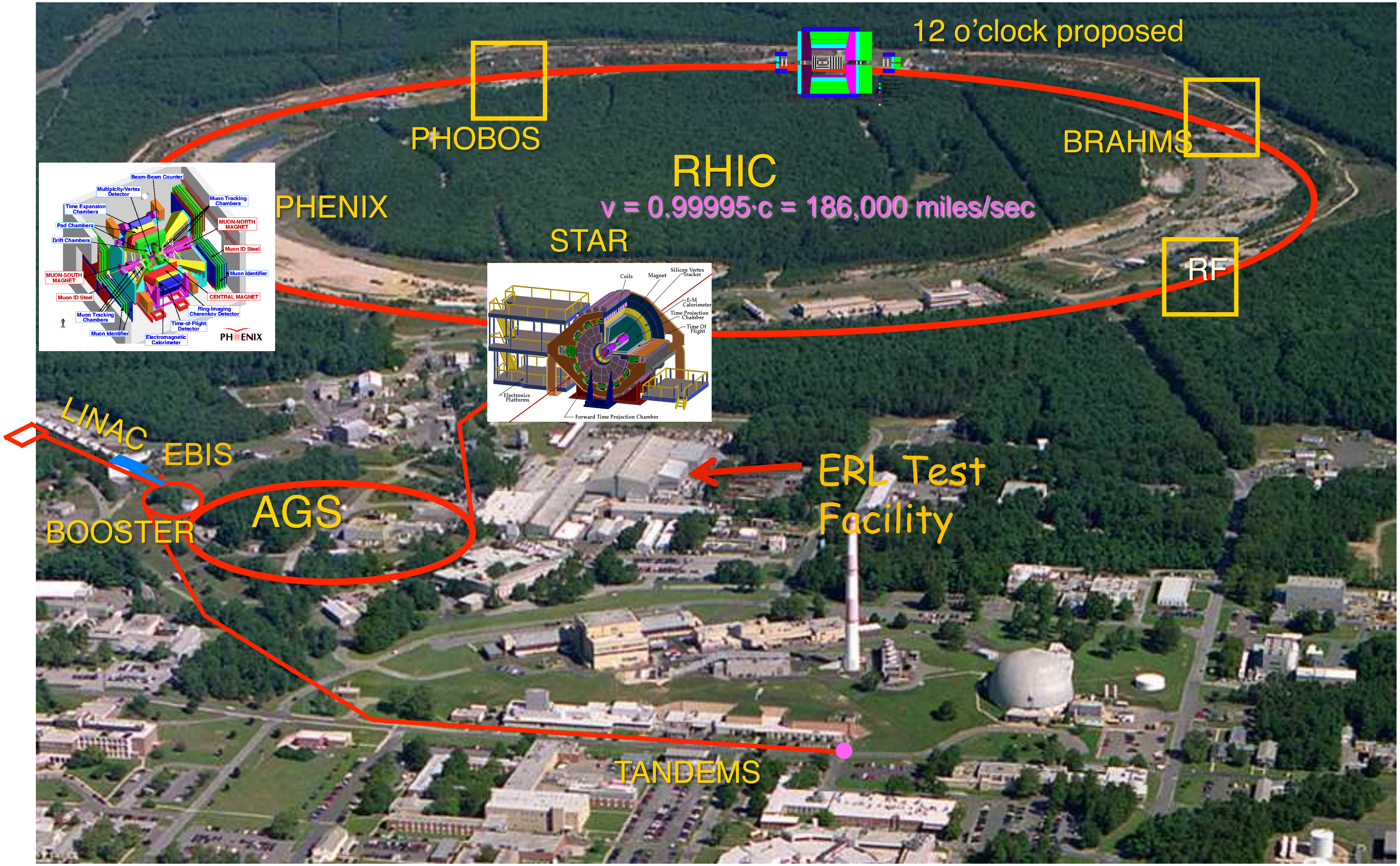


Polarized light ions
(He^3) 215 GeV/u

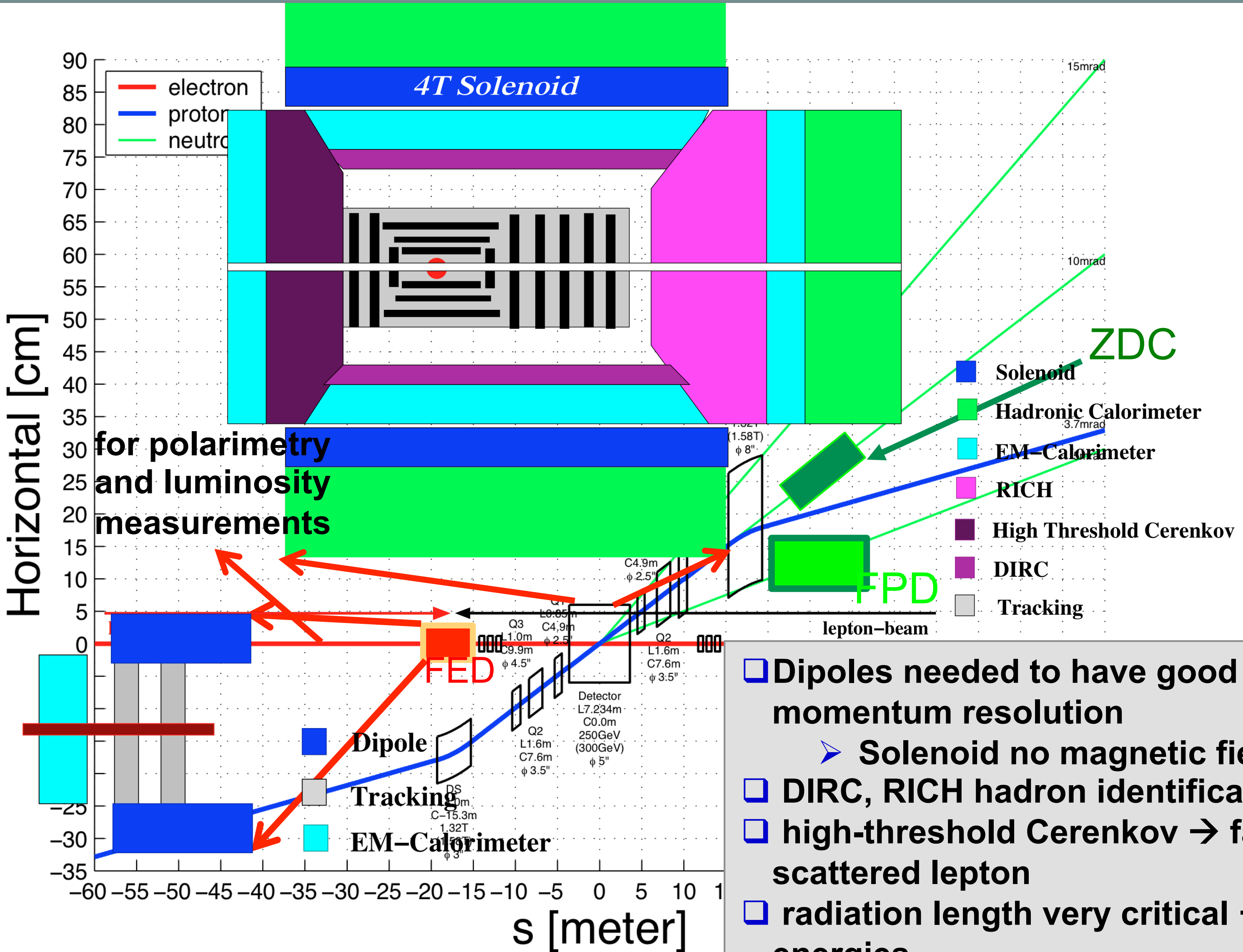
Center mass energy range: $\sqrt{s}$=28-200 GeV
longitudinal and transverse polarisation for p/He-3 possible

Mission: Studying the Physics of Strong Color Fields

The RHIC site @ BNL

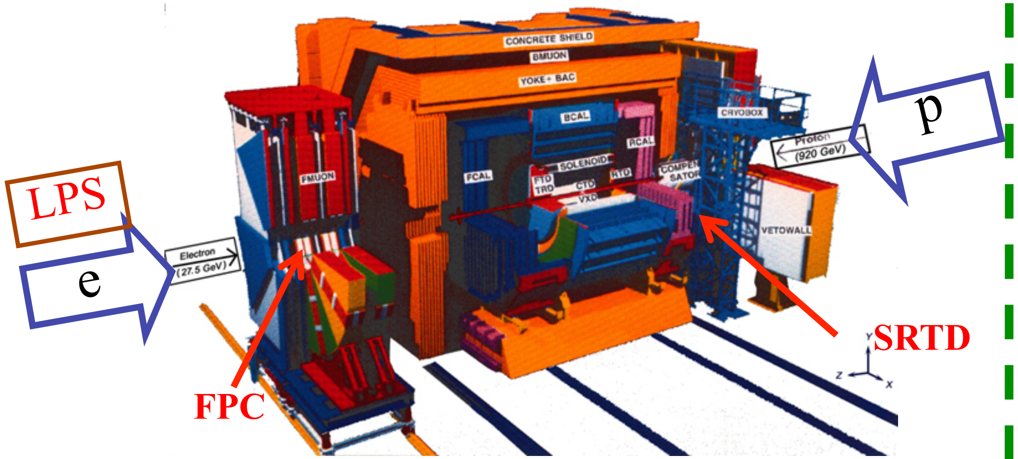


The EIC detector



- ❑ Dipoles needed to have good forward momentum resolution
  - ➢ Solenoid no magnetic field @ r ~ 0
- ❑ DIRC, RICH hadron identification → π, K, p
- ❑ high-threshold Cerenkov → fast trigger for scattered lepton
- ❑ radiation length very critical → low lepton energies

from ZEUS to new detector @ EIC

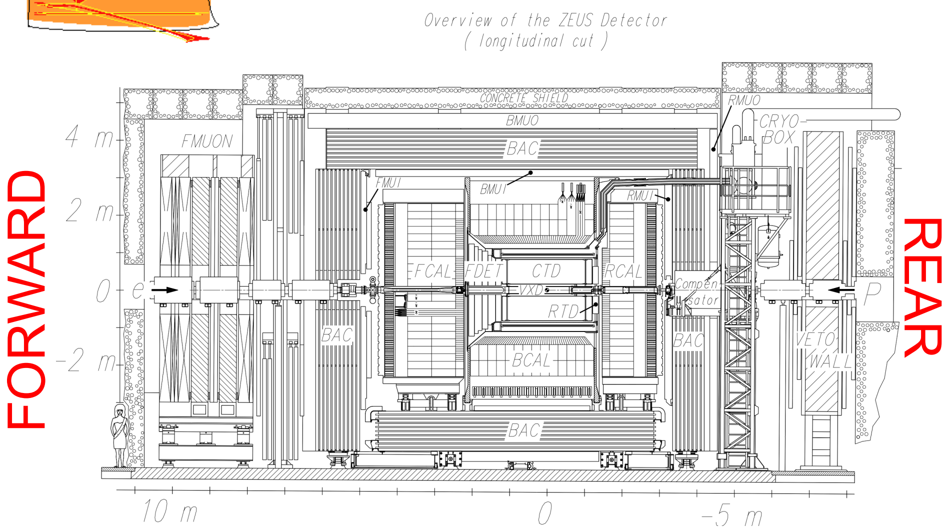


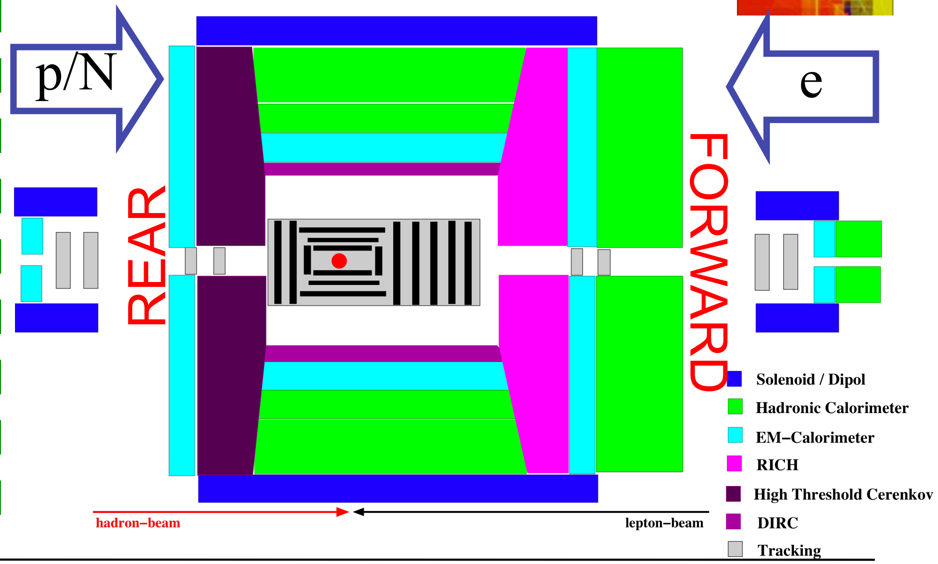
Similarities:

- Hermetic
- Asymmetric

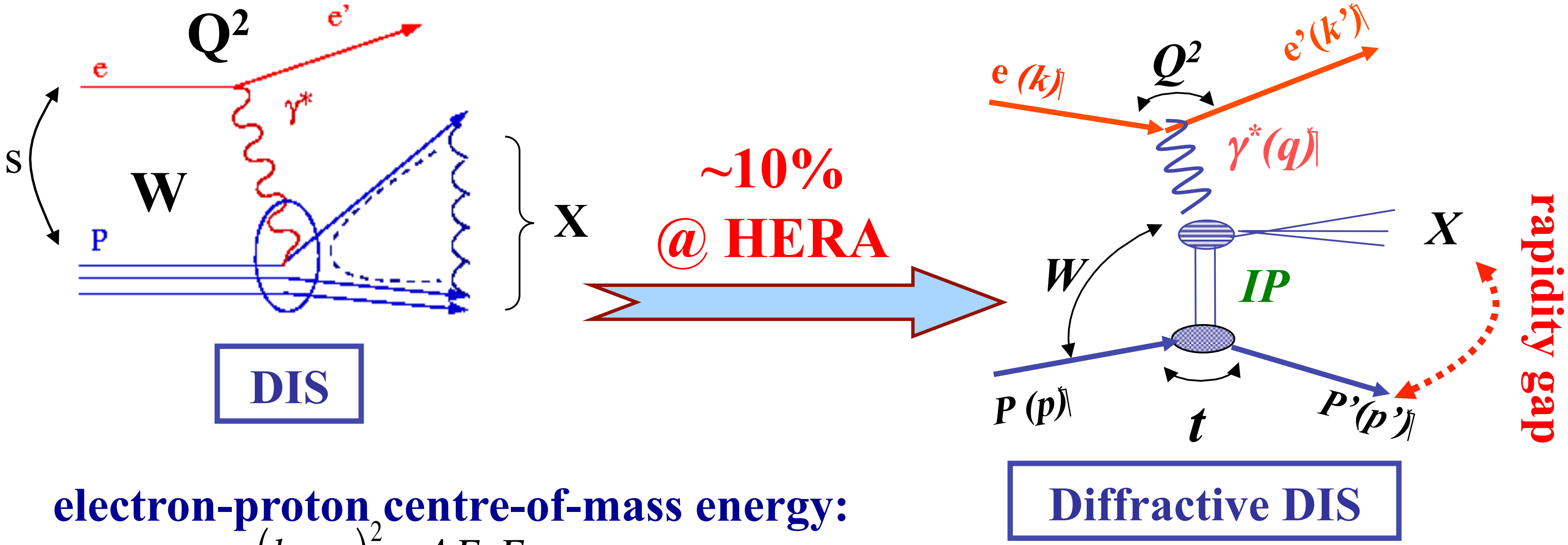
Important (possible) improvements:

- Central Tracking Detector
- better em calorimeter resolution
- Very forward calorimetry
- Rear Trackers!
- **Roman pots (crucial!)**





Diffraction in ep collisions



electron-proton centre-of-mass energy:

$$s = (k+p)^2 \approx 4E_e E_p$$

photon virtuality:

$$Q^2 = -q^2 = -(k-k')^2 \approx 4E_e E'_e \sin^2\frac{\theta}{2}$$

photon-proton centre-of-mass energy:

$$W^2 = (q+p)^2, \text{ where}: m_p < W < \sqrt{s}$$

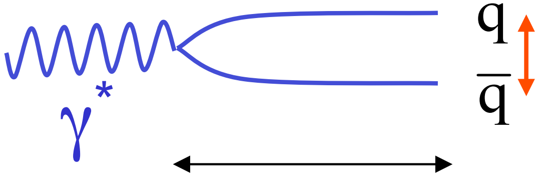
square 4-momentum at the *p* vertex:

$$t = (p' - p)^2$$

- ***p* escapes in the beam pipe**
- **no quantum numbers exchanged btw γ^* and *p* → no colour flux → large rapidity gap**
- **Providing a pQCD motivated description of strong interactions**

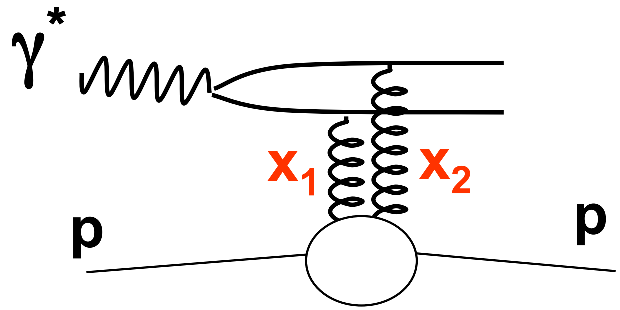
Diffraction in ep collisions

Before HERA diffraction was studied in hadron-hadron interactions

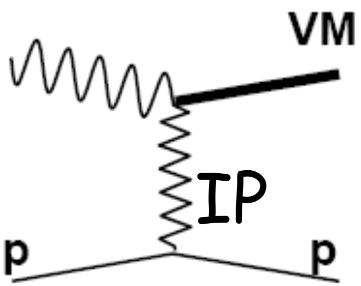


$$\propto \frac{1}{\sqrt{Q^2 + M_{q\bar{q}}^2}}$$

$$\propto E_\gamma \sim W^2 \sim 1/x$$

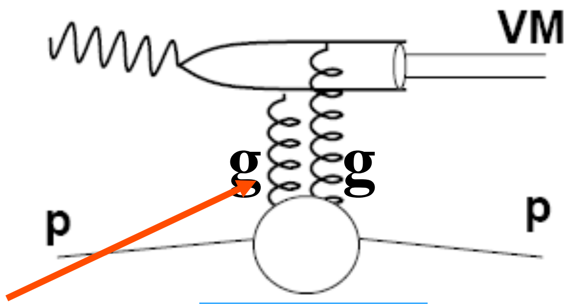


Exclusive diffractive production: ρ, φ, J/ψ, Y, γ



'soft'

gluon exchange
(pQCD)

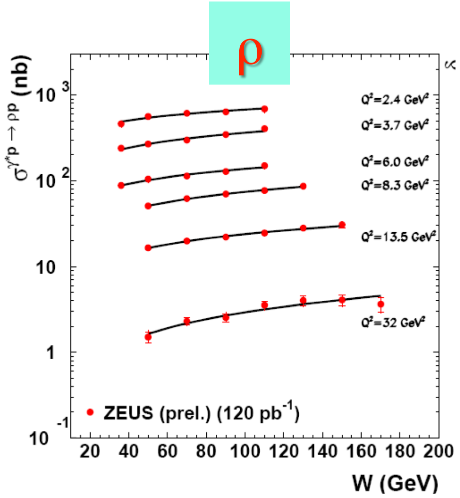


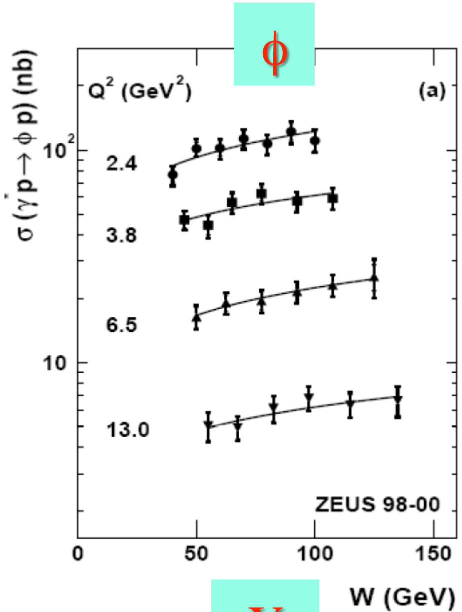
'hard'

$\sigma(W) \propto W^\delta$ δ Expected to increase from soft (~0.2, "soft Pomeron") to hard (~0.8, "hard Pomeron")

$\frac{d\sigma}{dt} \propto e^{-b|t|}$ *b* expected to decrease from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

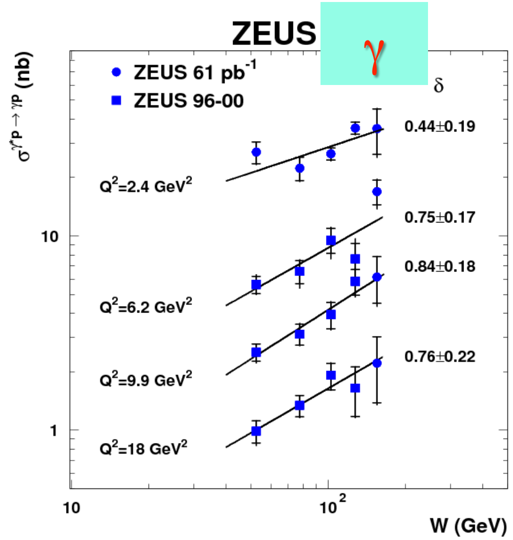
VM electroproduction: HERA measurements

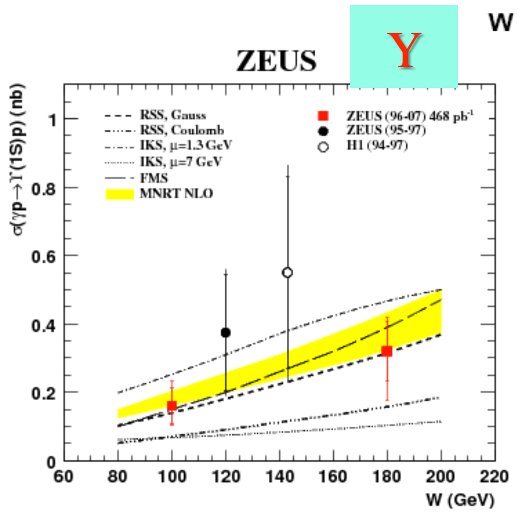


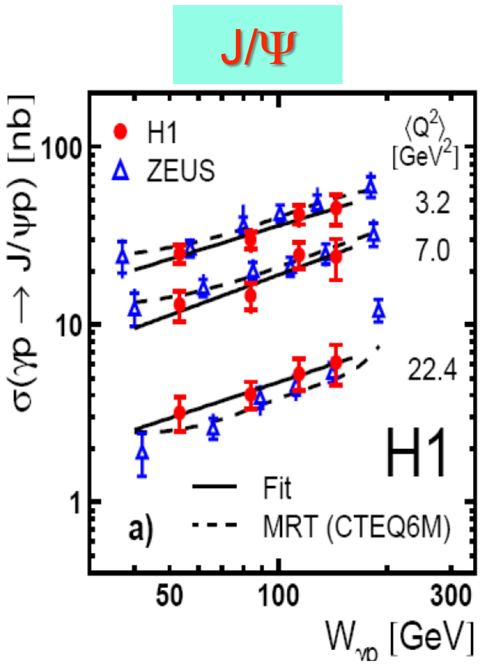


Large variety of processes to study dynamics versus scales: M_V^2, Q^2, t

Probe the transition to the hard regime

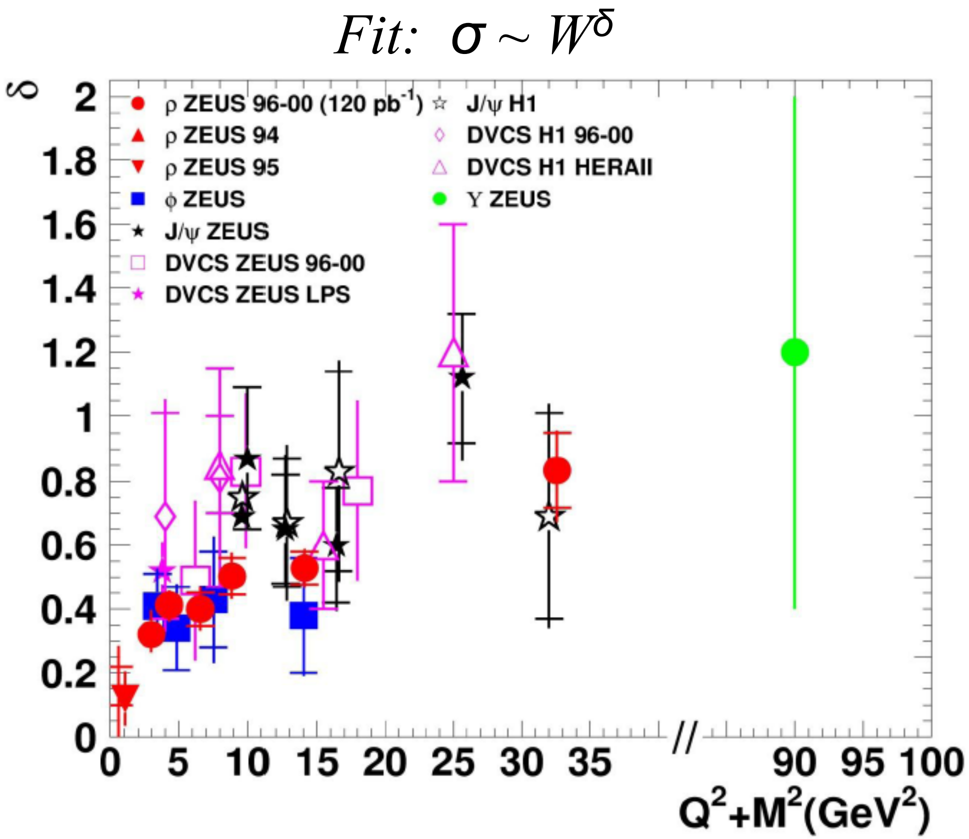


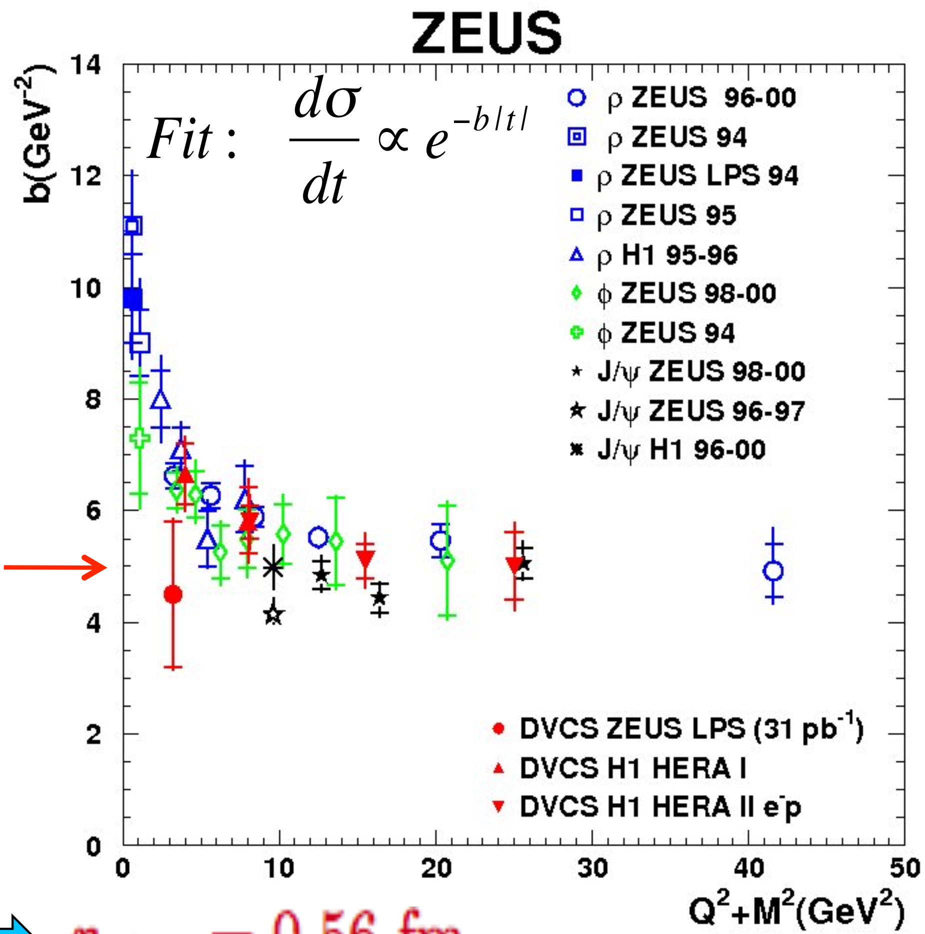




W-dependence: summary

Summary of the W,t-dependence for all VMs + DVCS measured at HERA

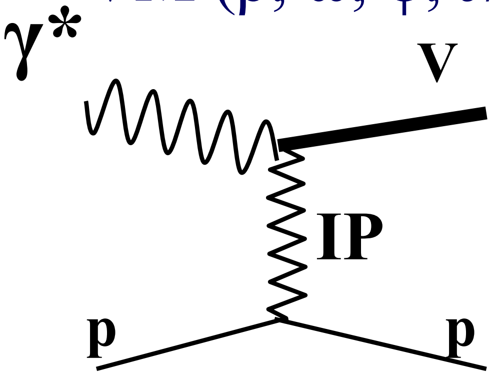




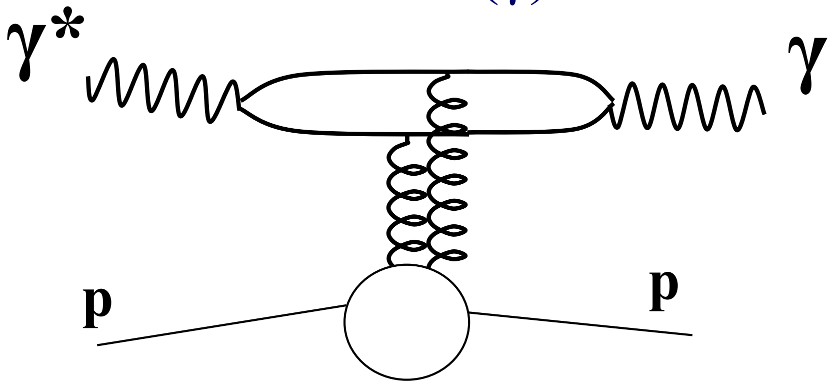
Size of the gluons: $\langle r^2 \rangle = 2 \cdot b \cdot (\hbar c)^2$ ➡ $r_{glue} = 0.56 \text{ fm}$

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Y)



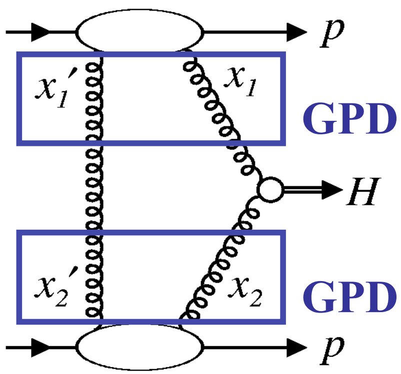
DVCS (γ)



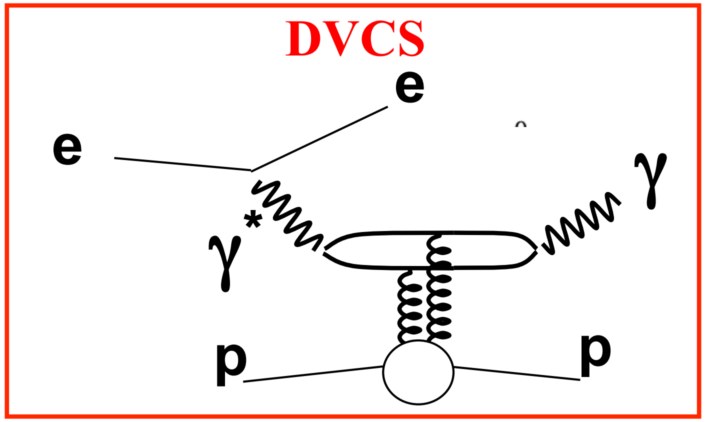
Scale: $Q^2 + M^2$ ⟷ Q^2

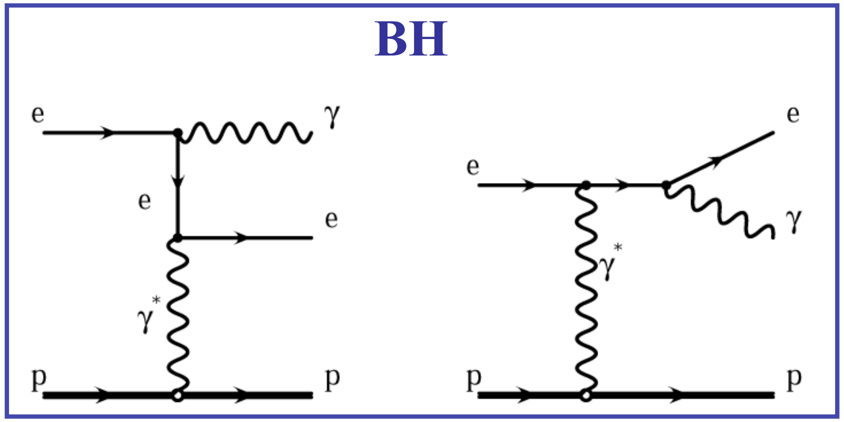
DVCS properties:

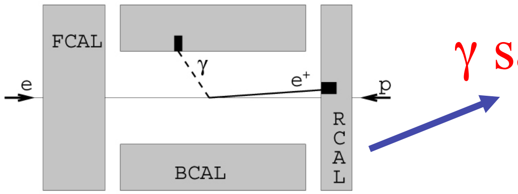
- **Similar to VM production, but γ instead of VM in the final state**
- **No VM wave-function involved**
- **Important to determine Generalized Parton Distributions sensible to the correlations in the proton**
- **GPD$_s$ are an ingredient for estimating diffractive cross sections at LHC**



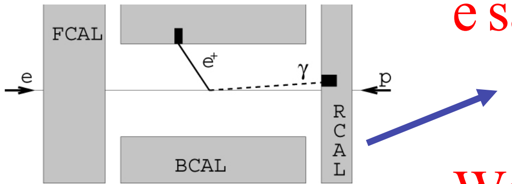
DVCS @ ZEUS - Strategy







γ sample: no tracks matching to the second candidate (DVCS+BH)

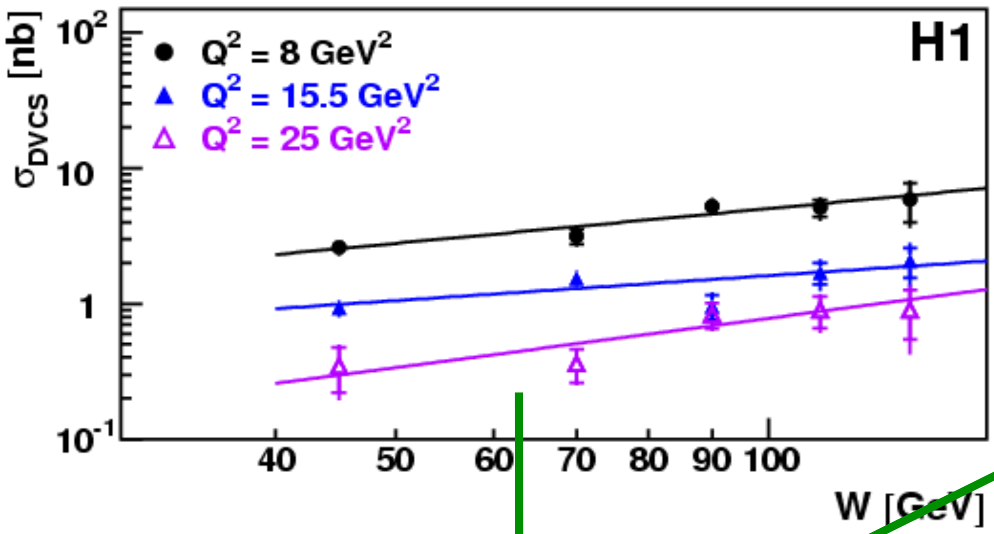


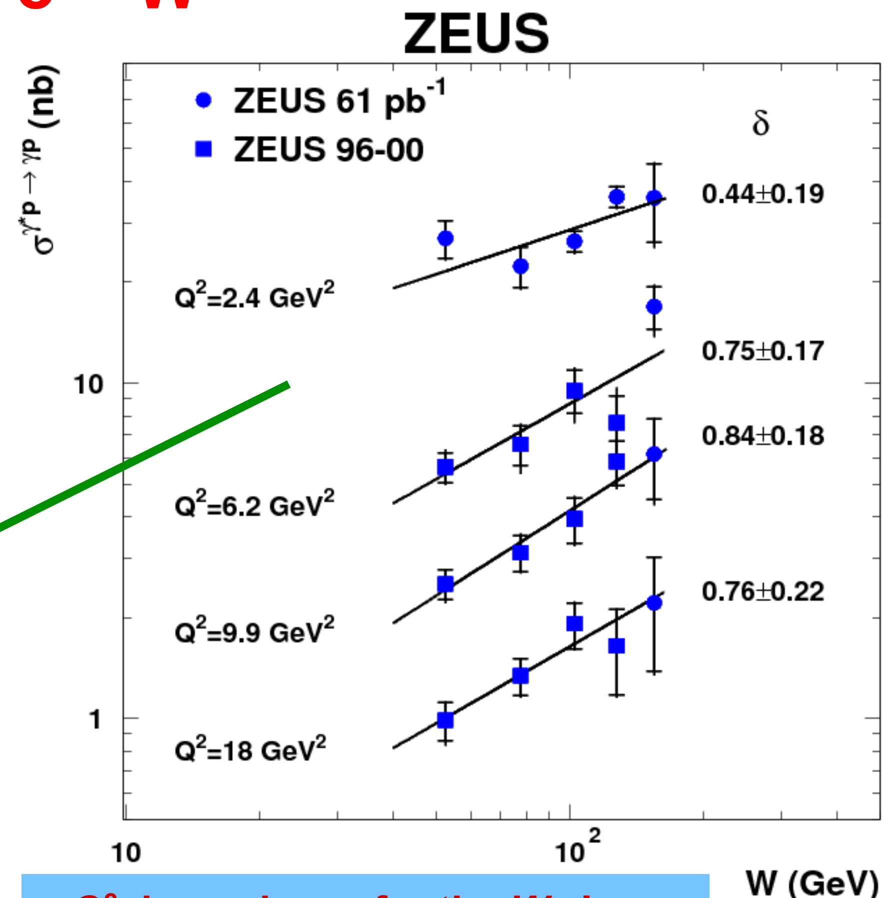
e sample: a track match to the second candidate (BH+ dilepton + J/ψ)

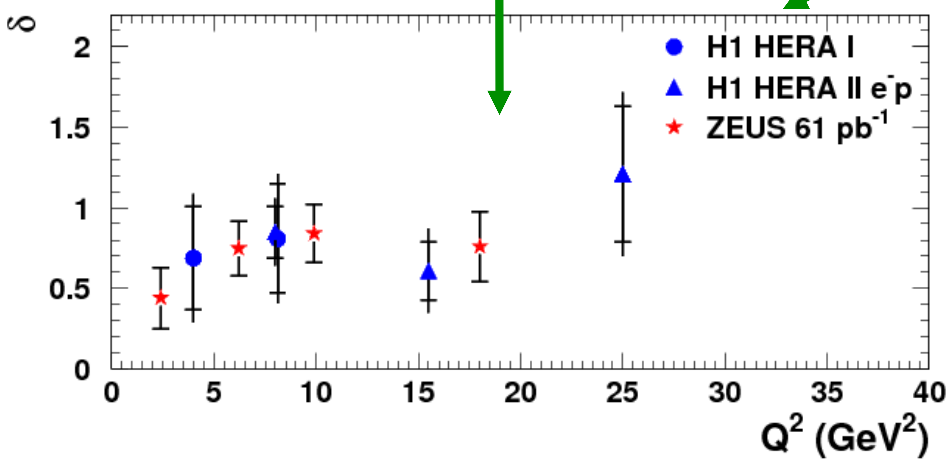
Wrong-sign sample: a negative track match to the second candidate (dilepton + J/ψ)

DVCS: *W*-dependence

Fit: $\sigma \sim W^{\delta}$







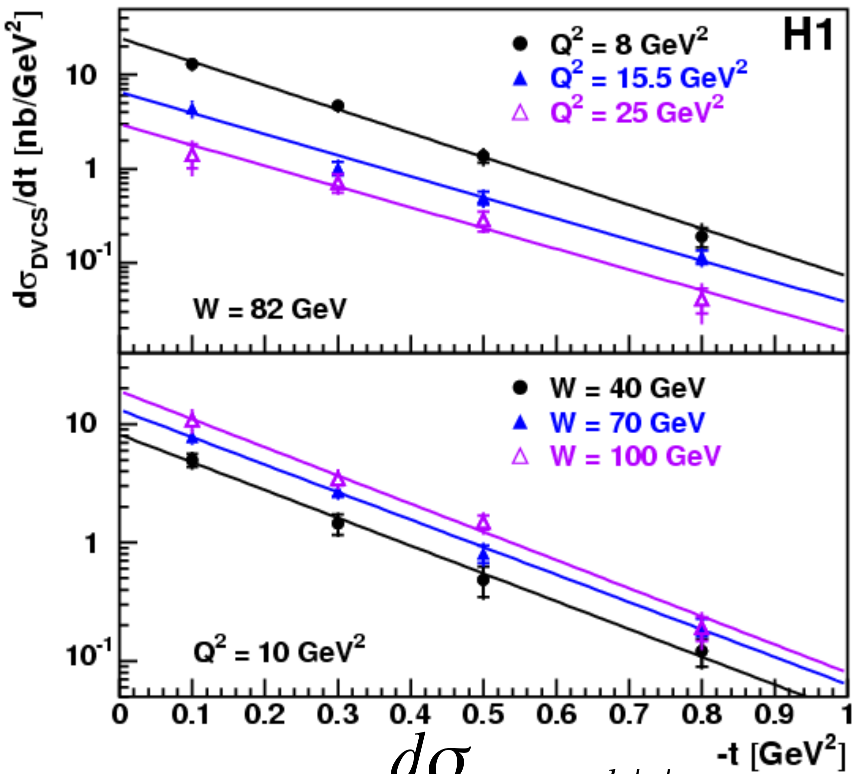
***Q*² dependence for the *W* slope not clear within the uncertainties!**

ZEUS: JHEP05(2009)108
H1: Phys.Lett.B659:796-806,2008

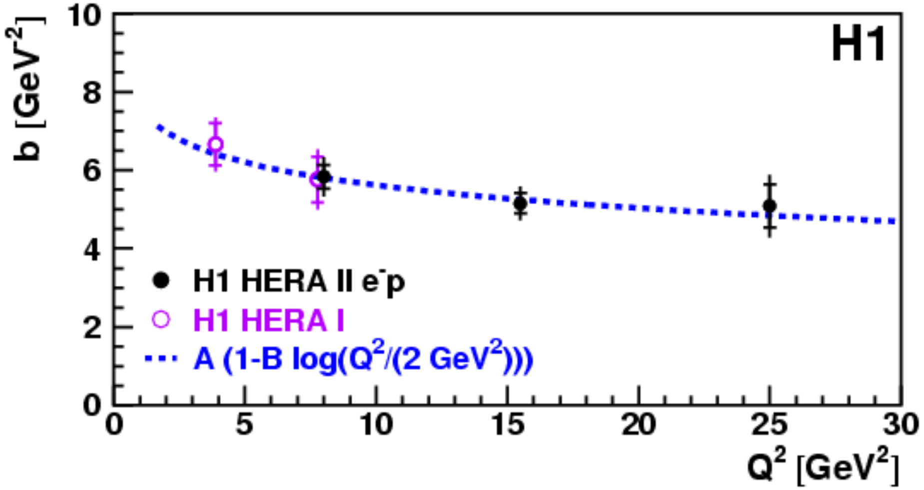
t dependence

The measured indirectly:

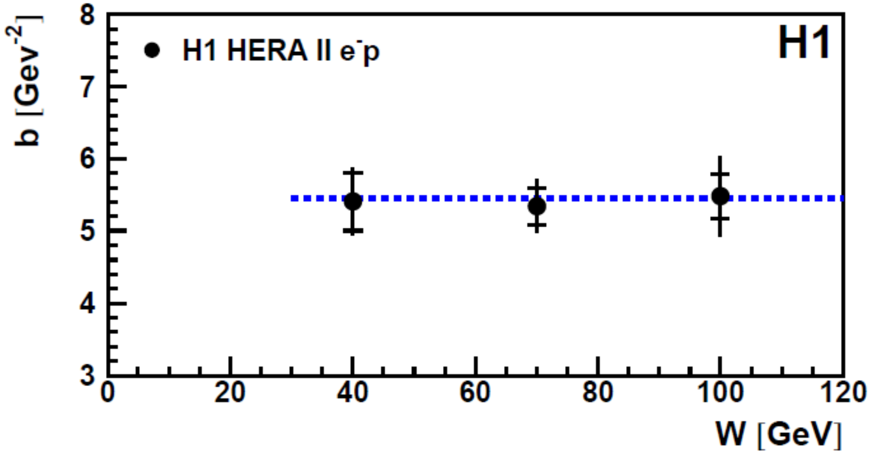
$$t \sim \left(P_{T\gamma}^2 + P_{T_e}^2\right)^2$$



$$Fit: \quad \frac{d\sigma}{dt} \propto e^{-b|t|}$$

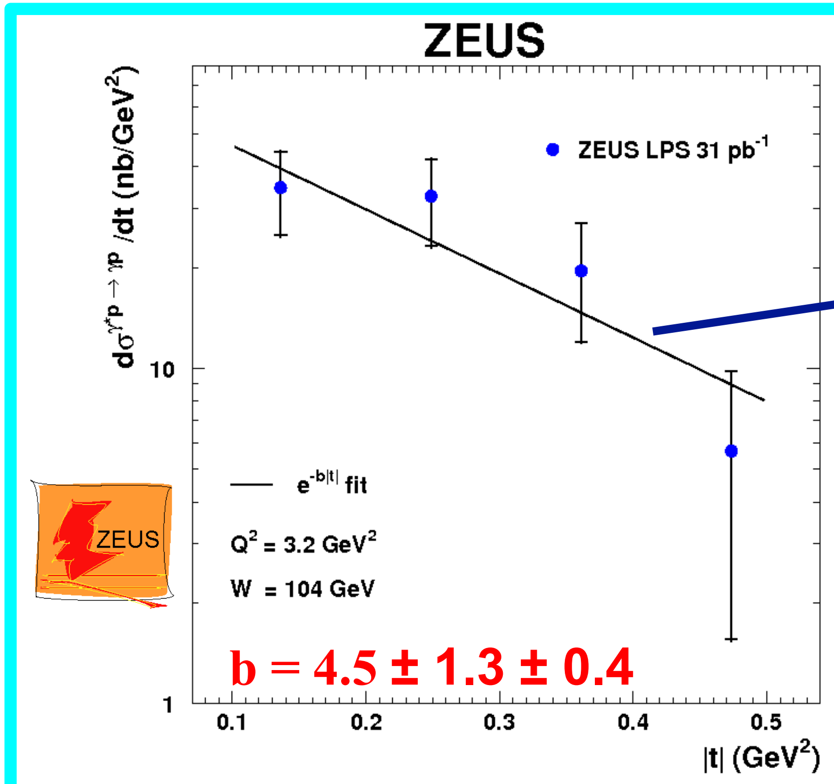


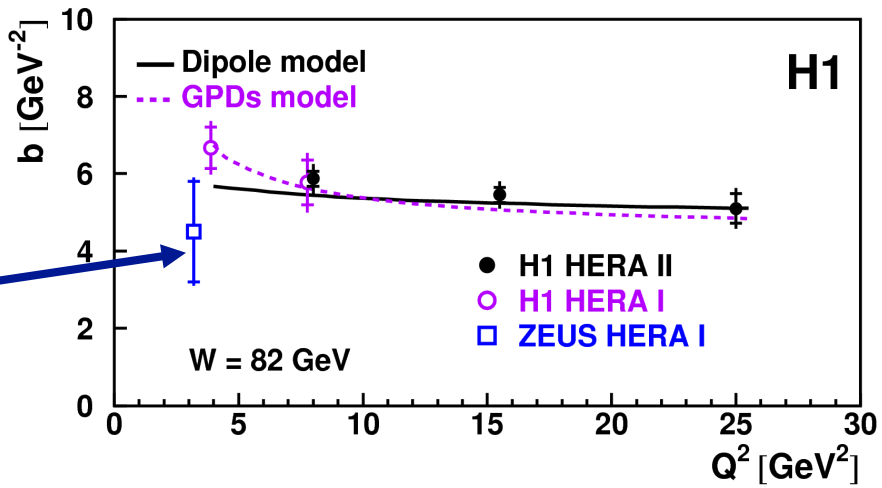
***b* decreases with increasing *Q*²**



No evidence for *W* dependence of *b*

t dependence

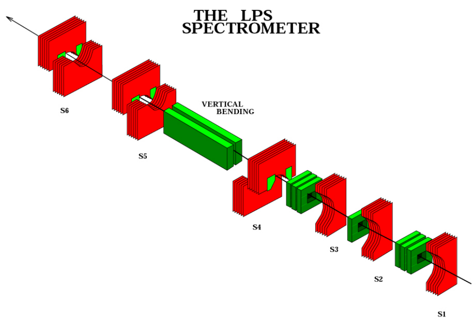




dσ/dt measured for the first time by a direct measurement of the outgoing proton 4-momentum using the LPS spectrometer

The ZEUS result is in agreement with H1

…nevertheless it seems to suggest a lower trend!



And at EIC…?

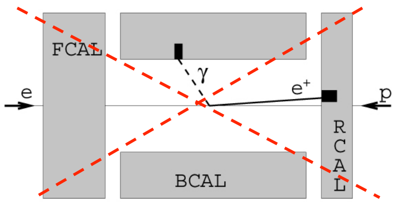
To successfully measure t indirectly from the electron and photon candidates

$$t \sim \left(P_{T_\gamma}^2 + P_{T_e}^2\right)^2 =$$

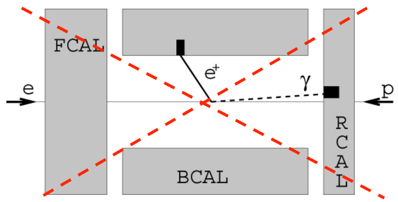
it is important:

❖ Tracker coverage (tracker has higher momentum resolution than Cal!)

Reso of the CTD @ ZEUS: $\sigma(pT)/pT = 0.0058pT \oplus 0.0065 \oplus 0.0014/pT$



DVCS/BH



BH

Red dashed line shows the CTD acceptance at ZEUS

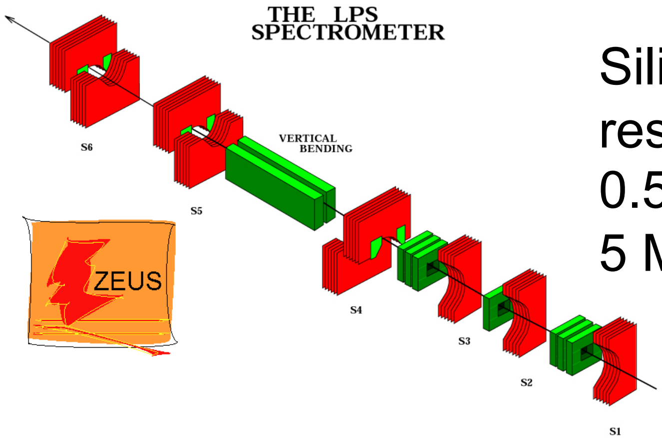
Always measure a track when we can -> better momentum resolution but not only… More acceptance for DVCS!! See the cut on $\theta_\gamma > 2.8$ rad

❖ High resolution em calorimetry (crucial! Remember that one particle is a photon!)

For ZEUS it was *σ(E)/E=0.18/√E* and was too week for good t resolution

And at EIC…?

But… is an indirect measurement of t really an issue for EIC?
We'll get roman pots in the forward region at EIC!



Silicon micro-strips resolution:
0.5% for P_L
5 MeV for P_T

$L = 27.77\ pb^{-1}$

55 events (DVCS + BH)

for eRHIC: $1.4\ 10^{34} *\ E_p/325\ cm^{-2}s^{-1}$
assuming 50% operations efficiency one week corresponds to:
$L(1\ w) = 0.5 * 604800(\text{s in a week}) * (1.4 \times 10^{34}\ cm^{-2}s^{-1}) = 4*10^{39}\ cm^{-2} = 4000pb^{-1}$

+ Roman Pots ⟶ ~ 7900 events/week !!

assuming the same acceptance ad LPS (~2%)

Calculations are absolutely not rigorous! But give an idea…

Pomeron trajectory

Regge-type: $$\frac{d\sigma}{dt}(W) = \exp(b_0 t)\cdot W^{2\left[2\alpha_{IP}(t)+2\right]}$$

First measured in h-h scattering

Linear Pomeron trajectory

$$\alpha(t) = \alpha(0) + \alpha'(t)t$$

$\alpha(0)$ and α' are foundamental parameters to represent the basic features of strong interactions

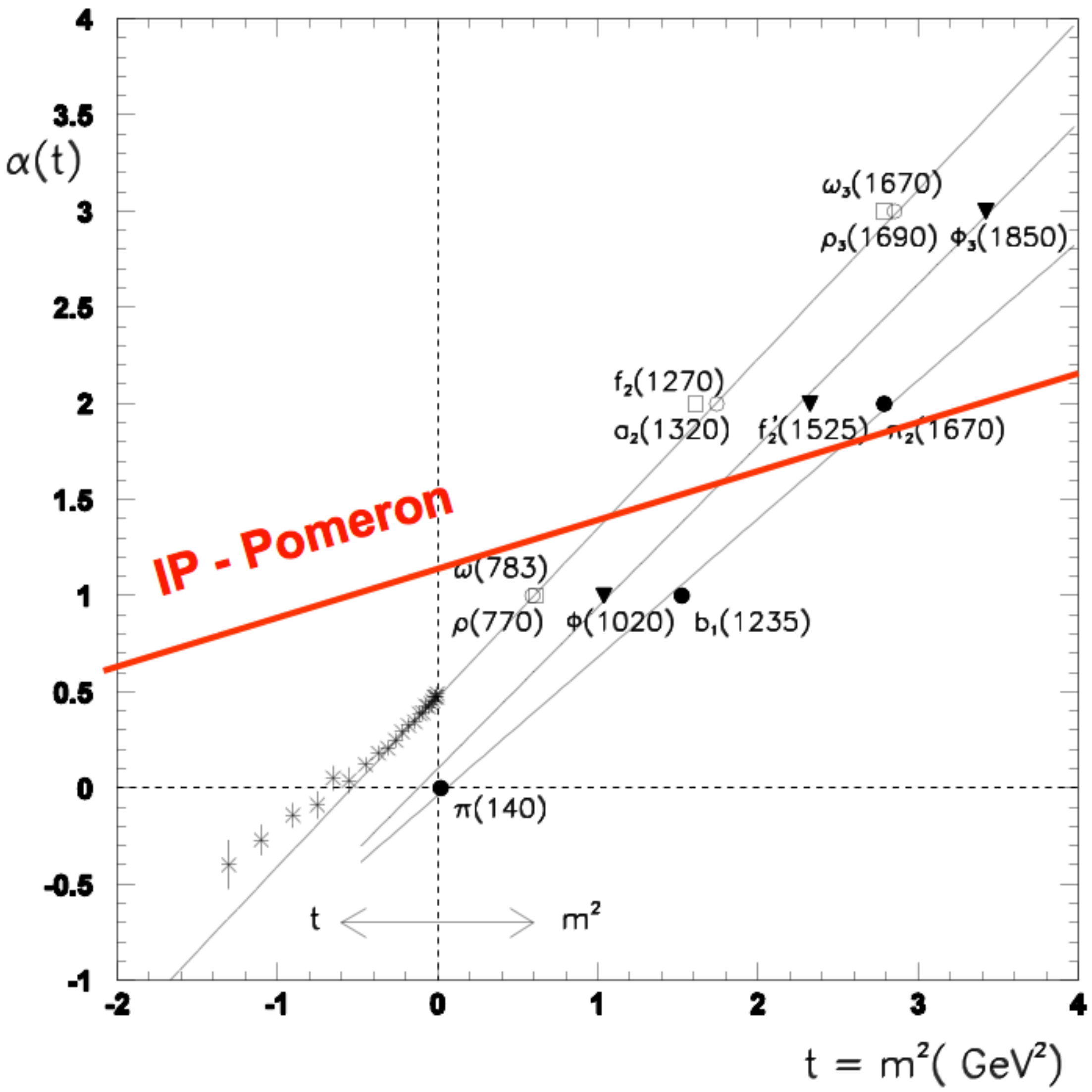
Soft Pomeron values
$\alpha(0) \approx 1.09$
$\alpha' \approx 0.25$

$\alpha(0)$: determines the energy dependence of the diff. Cross section

$$\frac{d\sigma}{dt} \propto \exp(b_0 t)\cdot W^{4\alpha(t)-4} = W^{\underline{4\alpha(0)}-4}\cdot \exp(bt); \qquad b = b_0 + 4\underline{\alpha'}\ln(W)$$

α': determines the energy dependence of the transverse extention system

Pomeron trajectory in hh collisions



$$\alpha(t) = \alpha(0) + \alpha'(t)t$$

$$\sigma_{tot}(h-h) = As^{\alpha_{IP}(0)-1} + Bs^{\alpha_{IR}(0)-1}$$

Pomeron:

$\alpha_{IP}(t) = 1.09 + 0.25t$

Reggeon:

$\alpha_{IR}(t) = 0.45 + t$

Pomeron trajectory in ep collisions

Trajectory varies with the scale

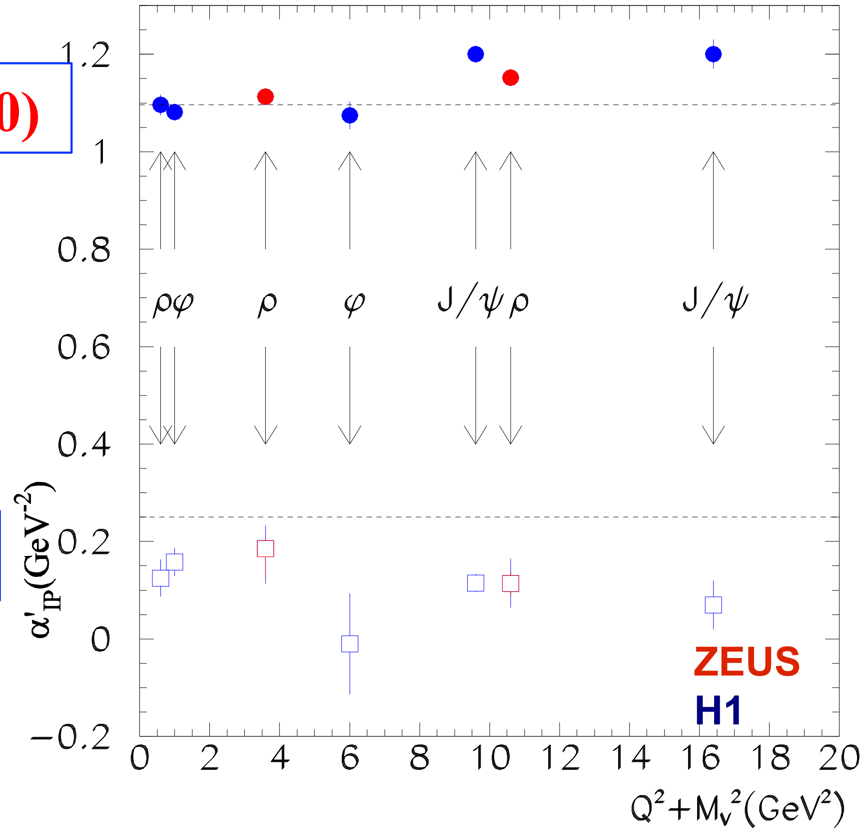
$\alpha_{IP}(t) = 1.09 + 0.25t$ measured in hh scattering

In electron-proton interactions:

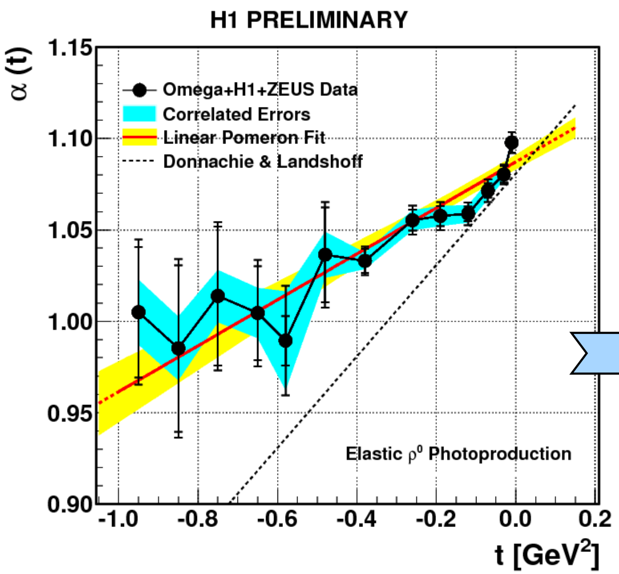
- As the scale gets harder the intercept grows up to 1.2
- The Pomeron slope is around ~0.1

α(0)

α'



H1



ρ (light VM); elastic production (low |t|):

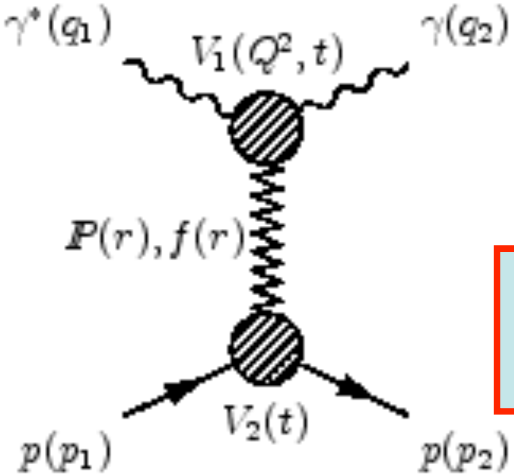
$\alpha(0) = 1.087 \pm 0.003 \pm 0.003$

$\alpha' = 0.126 \pm 0.013 \pm 0.012\ GeV^{-2}$

A model for the amplitude

M. Capua, S. Fazio, R. Fiore, L. Jenkovszky, F Paccanoni

Published in: Physics Letters B645 (Feb. 2007) 161-166



$$V_1 = e^{b\beta((z))}$$

$$V_2 = e^{b\alpha(t)}$$

A new variable is introduced: $z = t - Q^2$

Applications for the model can be:

- **Study of various extreme regimes of the scattering amplitude vs *Q2, W, t* (perturbative –> unperturbative QCD)**
- **Study of GPD$_s$**

DVCS amplitude: $A\left(s,t,Q^2\right)_{\gamma^* p\to\gamma p} = -A_0 V_1\left(t,Q^2\right) V_2(t)\left(-is/s_0\right)^{\alpha(t)}$

the *t* dependence at the vertex *pIPp* is introduced by: $\alpha(t) = \alpha(0) - \alpha_1 \ln\left(1-\alpha_2 t\right)$

the vertex *γ*IPγ* is introduced by the trajectory: $\beta(z) = \beta(0) - \beta_1 \ln\left(1-\beta_2 z\right)$

indicating with: $L = \ln\left(-is/s_0\right)$ **the DVCS amplitude can be written as:**

$$A\left(s,t,Q^2\right)_{\gamma^* p\to\gamma p} = -A_0 e^{b\alpha(t)} e^{b\beta(z)}\left(-is/s_0\right)^{\alpha(t)} = -A_0 e^{(b+L)\alpha(t)+b\beta(z)}$$

$$Q^2 \rightarrow \tilde{Q}^2 = Q^2 + M_V^2$$

Model is general:
it can be easily extended to VMP

S. F., R. Fiore, L.L. Jenkovszky, A. Lavorini

$$\tilde{Q}^2 = Q^2 + M_i^2 \quad \text{where} \quad i = 0 \ for \ DVCS \ and \ M_\rho \ or \ M_{J/\psi} \ for \ \rho \ or \ J/\psi \ VM$$

$$\frac{d\sigma(s,t,\tilde{Q}^2)}{dt} = \frac{\pi}{s^2}|A(s,t,\tilde{Q}^2)|^2$$

$$\sigma_{el}^{1P}(s,\tilde{Q}^2) \approx \left[\frac{1}{B(s,t,\tilde{Q}^2)}\frac{d\sigma(s,t,\tilde{Q}^2)}{dt}\right]_{t=0} = \frac{2\pi\alpha'|A_0|^2(s/s_0)^{(\alpha_0/2)}}{\left(1+\alpha_2\tilde{Q}^2\right)^{(2b_1\alpha_1)+1}} \cdot b_2\left[b_1 + \log_e(s/s_0)\right]$$

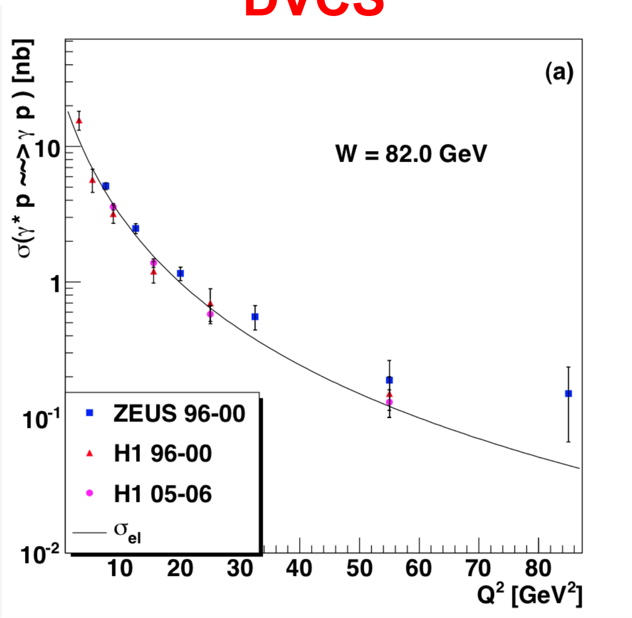
Fixed parameters

Single Pomeron Model

$\alpha_0 = \beta_0$	$\alpha_1 = \beta_1$	$\alpha_2 = \beta_2$	b_1	s_0
1.09	2.00	0.125	2.00	1.00

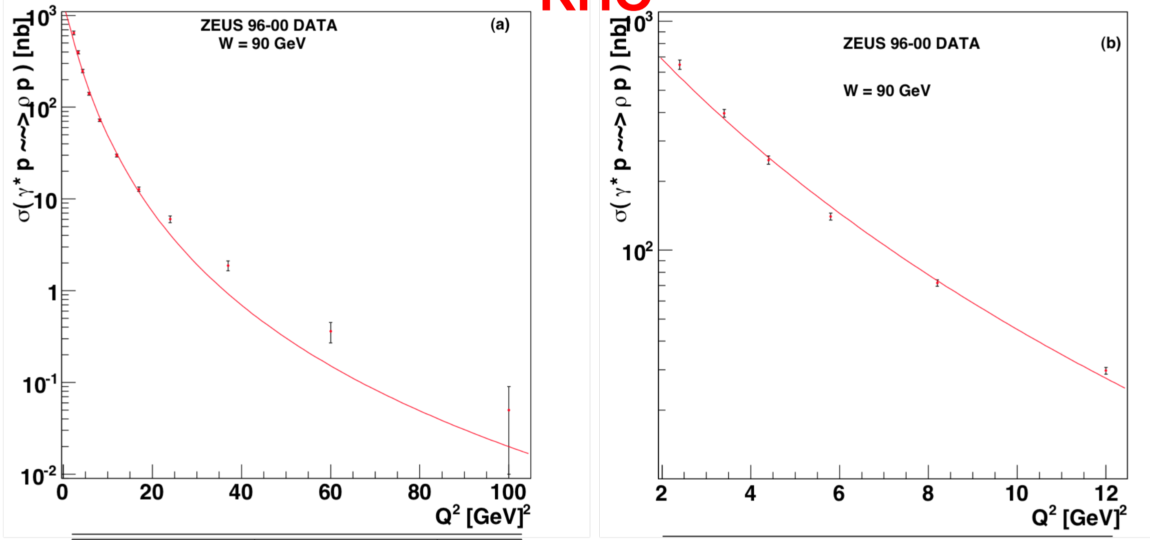
Table 1: *Parameters values for Single Pomeron Model.*

DVCS



b_2	$\|A_0\|^2$	$\tilde{\chi}^2$
0.64 ± 0.03	0.13 ± 0.01	1.58

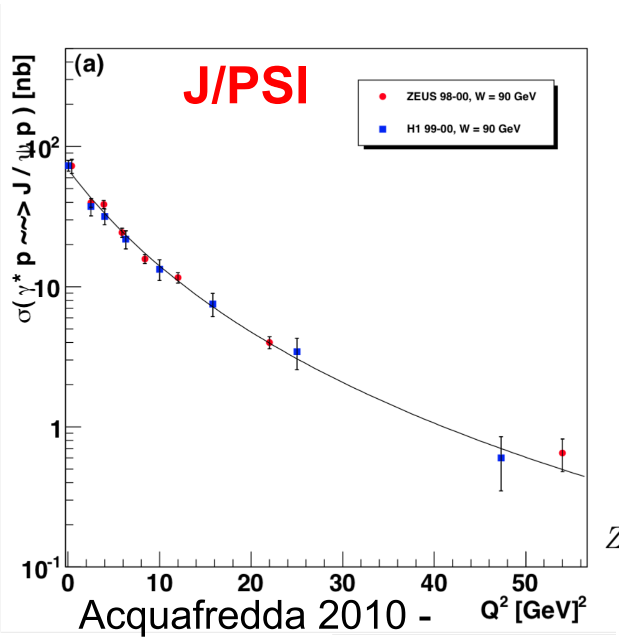
RHO



b_2	$\|A_0\|^2$	$\tilde{\chi}^2$
1.10 ± 0.02	9.73 ± 0.45	9.52

b_2	$\|A_0\|^2$	$\tilde{\chi}^2$
1.19 ± 0.02	1.21 ± 0.62	5.85

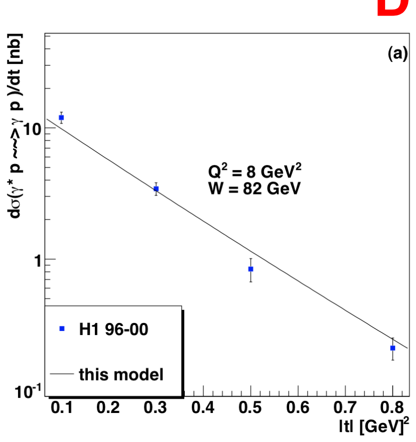
J/PSI

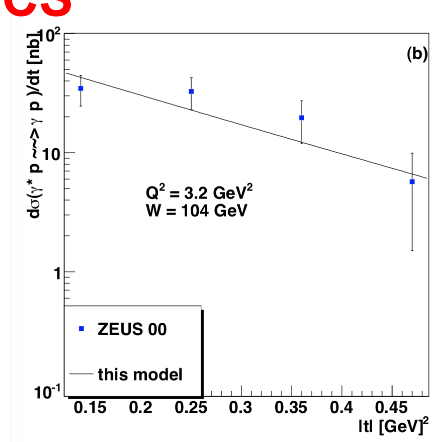


b_2	$\|A_0\|^2$	$\tilde{\chi}^2$
0.87 ± 0.03	5.16 ± 0.64	0.54

ZEUS 98-00; H1 99-00; $W = 90.0$ GeV; $t = 0.17$.

DVCS





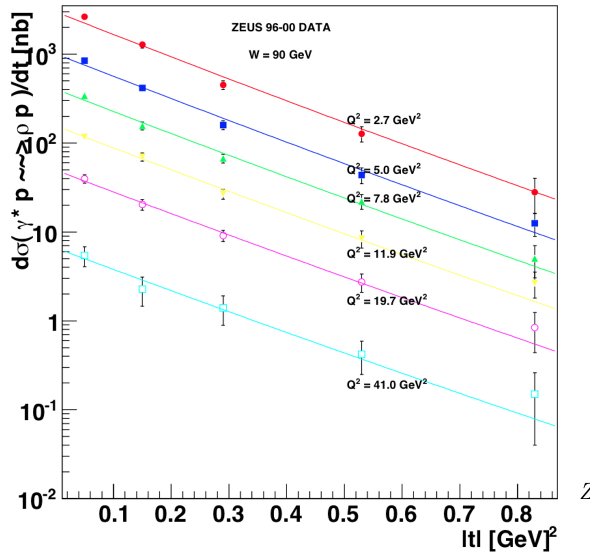
$(a)\ \ d\sigma_{(\gamma^*\ p\ -> \ \gamma\ p)}/dt\ \ (\lvert t\rvert)$		
b_2	$\lvert A_0\rvert^2$	$\tilde{\chi}^2$
0.64	0.021 ± 0.001	2.46

Table 5: *H1 96-00; Q^2 = 8.0 GeV^2 ; W = 82.0 GeV ; b_2 = 0.64.*

$(b)\ \ d\sigma_{(\gamma^*\ p\ -> \ \gamma\ p)}/dt\ \ (\lvert t\rvert)$		
b_2	$\lvert A_0\rvert^2$	$\tilde{\chi}^2$
0.64	0.043 ± 0.008	0.89

Table 6: *ZEUS 00 ; Q^2 3.2 GeV^2 ; W = 104.0 GeV ; b_2 = 0.64.*

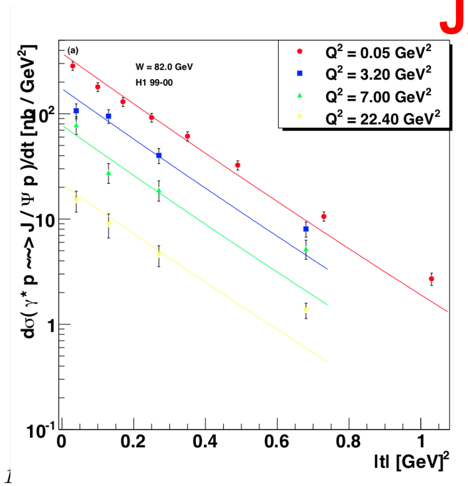
RHO

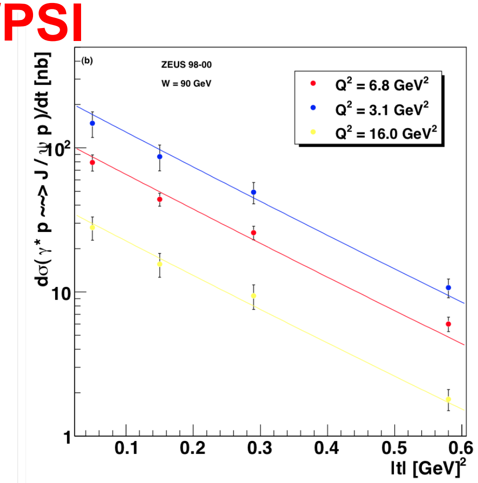


$d\sigma_{(\gamma^*\ p\ ->\rho\ p)}/dt\ \ (\lvert t\rvert)$		
Q^2	$\lvert A_0\rvert^2$	$\tilde{\chi}^2$
2.7	0.89 ± 0.04	2.23
5.0	0.49 ± 0.02	1.52
7.8	0.42 ± 0.02	1.28
11.9	0.31 ± 0.02	0.66
19.7	0.32 ± 0.02	0.29
41.0	0.6 ± 0.1	0.29

ZEUS 96-00; W = 90.0 GeV; b_2 = 1

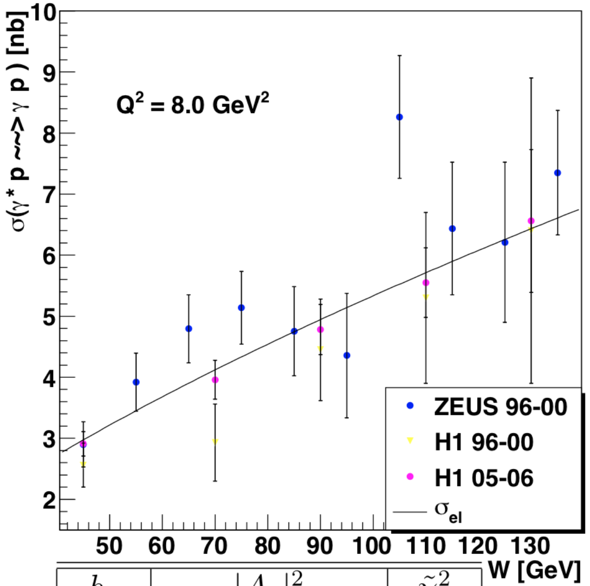
J/PSI





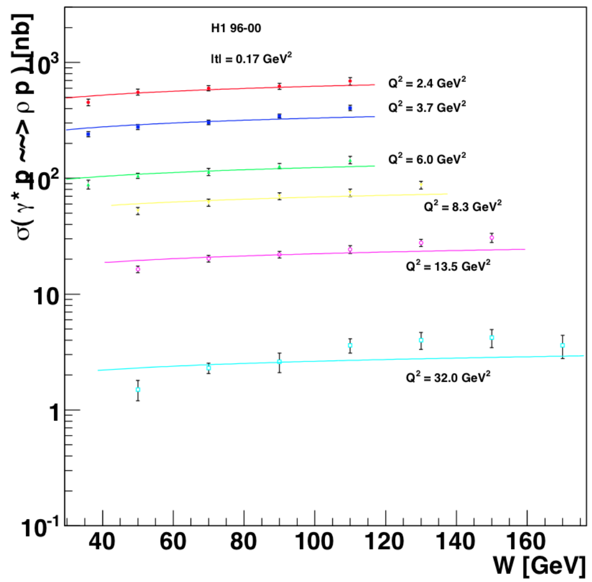
Q^2	$\lvert A_0\rvert^2$	$\tilde{\chi}^2$
3.1	0.74 ± 0.07	0.90
6.8	0.67 ± 0.04	2.93
16.0	0.70 ± 0.06	0.55

DVCS

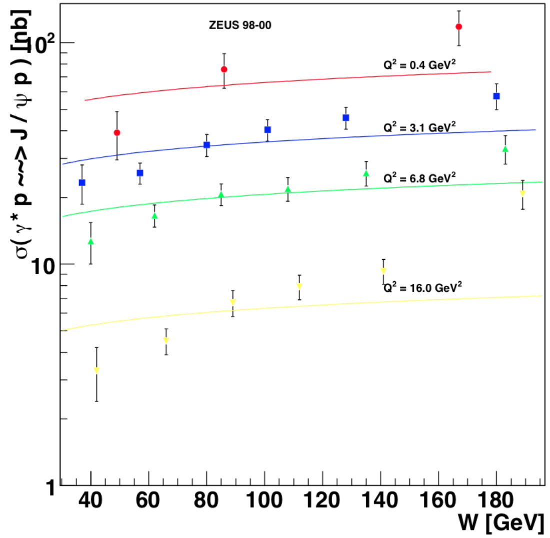


b_2	$\|A_0\|^2$	$\tilde{\chi}^2$
0.64	0.141 ± 0.004	1.03

RHO



J/PSI



Model does not describe σ(W) at large scale (Q^2+M^2) values with a single Pomeron contribution

Extension of the model

S. F., R. Fiore, L.L. Jenkovszky, A. Lavorini

We may consider the Pomeron as an "effective" one containing the contribution from many particles, each one with a Q^2-independent trajectory

$$\boxed{A_{tot} = A_s + h \cdot A_h}$$

$$A_i\left(s,t,Q^2\right)_{\gamma^* p \to \gamma p} = -A_0 e^{b\alpha(t)} e^{b\beta(z)} \left(-is/s_0\right)^{\alpha(t)} = -A_0 e^{(b+L)\alpha(t) + b\beta(z)}$$

$$\alpha_i(t) = \alpha(0) - \alpha_1 \ln\left(1 - \alpha_2 t\right)$$

$$\beta_i(z) = \beta(0) - \beta_1 \ln\left(1 - \beta_2 z\right)$$

i = soft; hard

Soft Pomeron:

$$\alpha_{soft}(t) = 1.08 + 0.25t$$

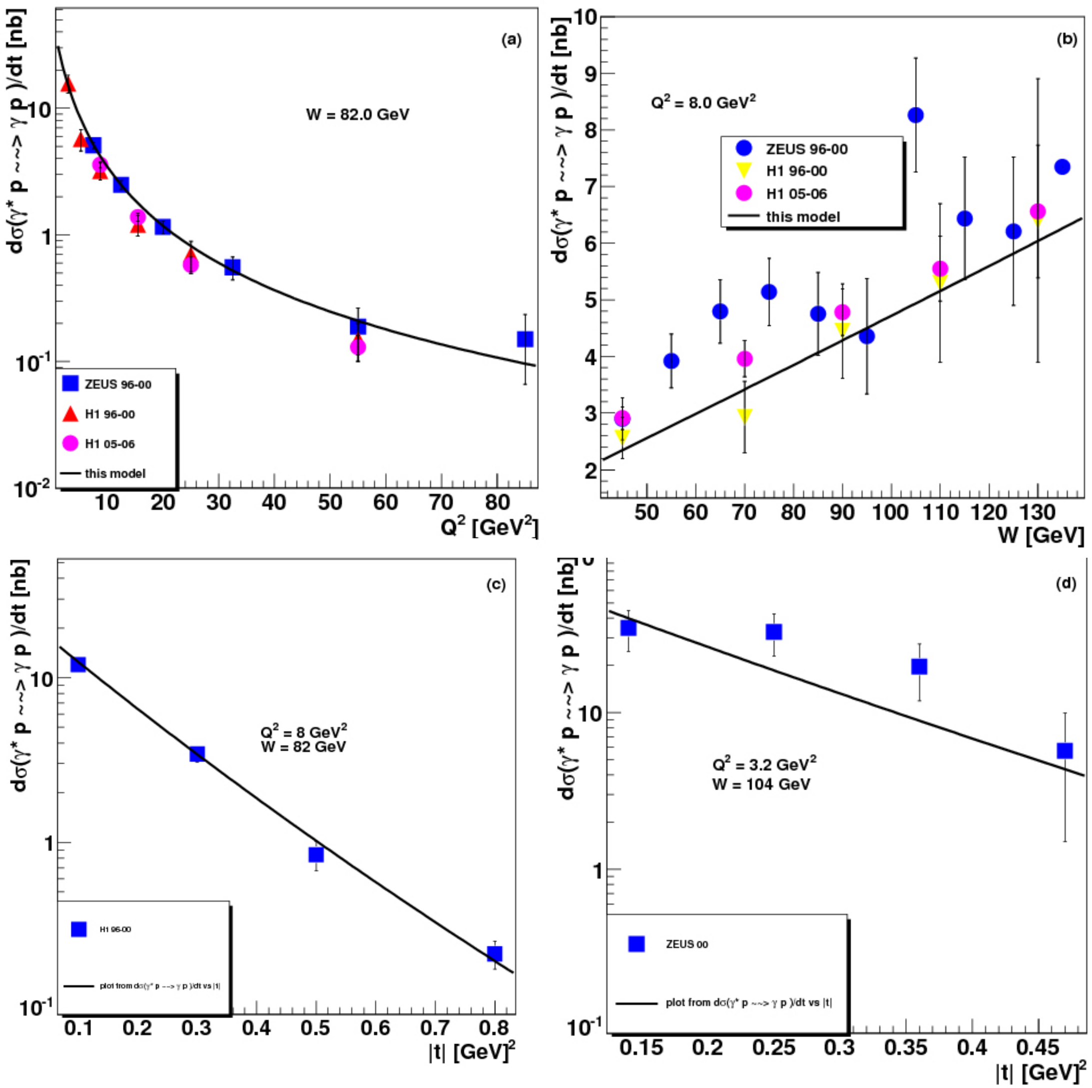
Hard Pomeron:

$$\alpha_{hard}(t) = 1.30 + 0.02t$$

Now we have two "universal" Pomerons!

DVCS (two Pomerons contribution)

DVCS data collected at HERA



$$\boxed{A_{tot} = A_s + h \cdot A_h}$$

Reggeon contribution found to be negligible at the HERA energy scale

Model compared to dσ/dt with all param. fixed and anly norm. free

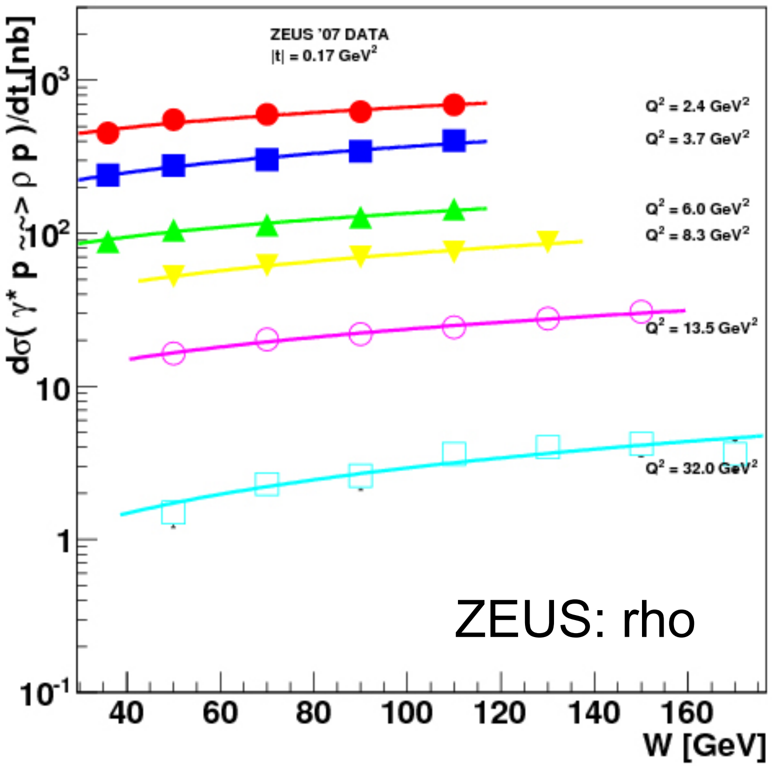
dσ/dt agreement with H1 improved

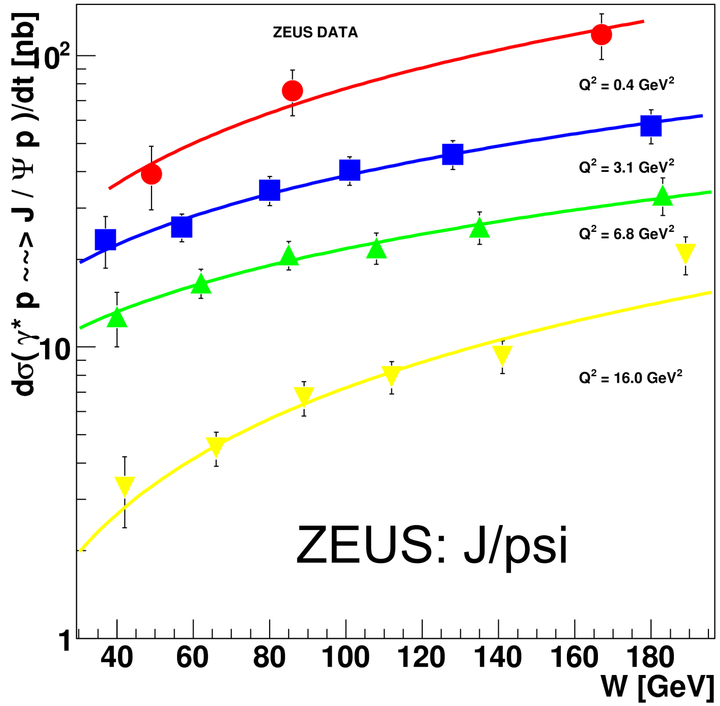
$\alpha_s(0) = 1.09 \qquad \alpha'_s = 0.25$

$\alpha_h = 1.30 \qquad \alpha'_h = 0.02$

VM (two Pomerons contribution)

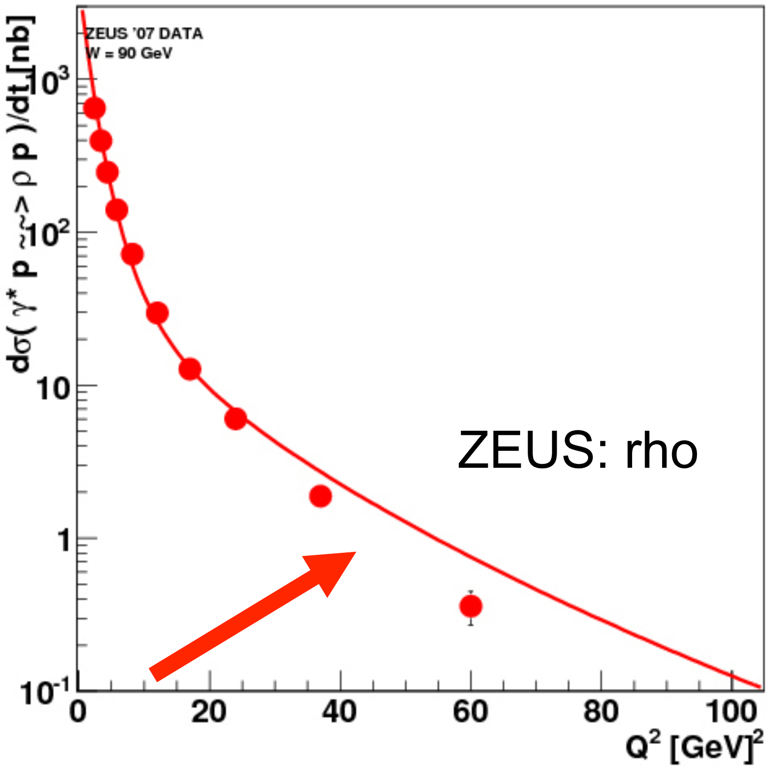
$$\boxed{A_{tot} = A_s + h \cdot A_h}$$

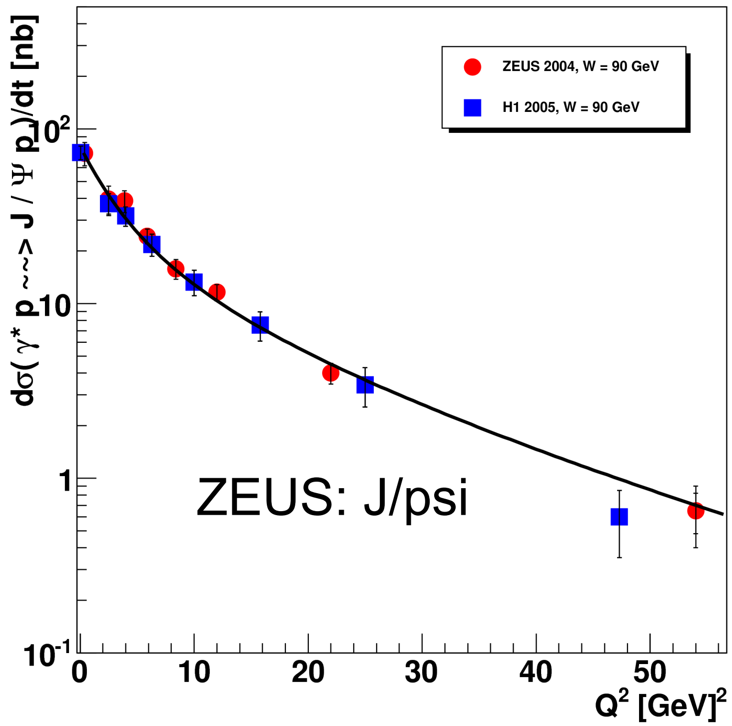




Successful description of the total xsec. in energy

VM (two Pomerons contribution)

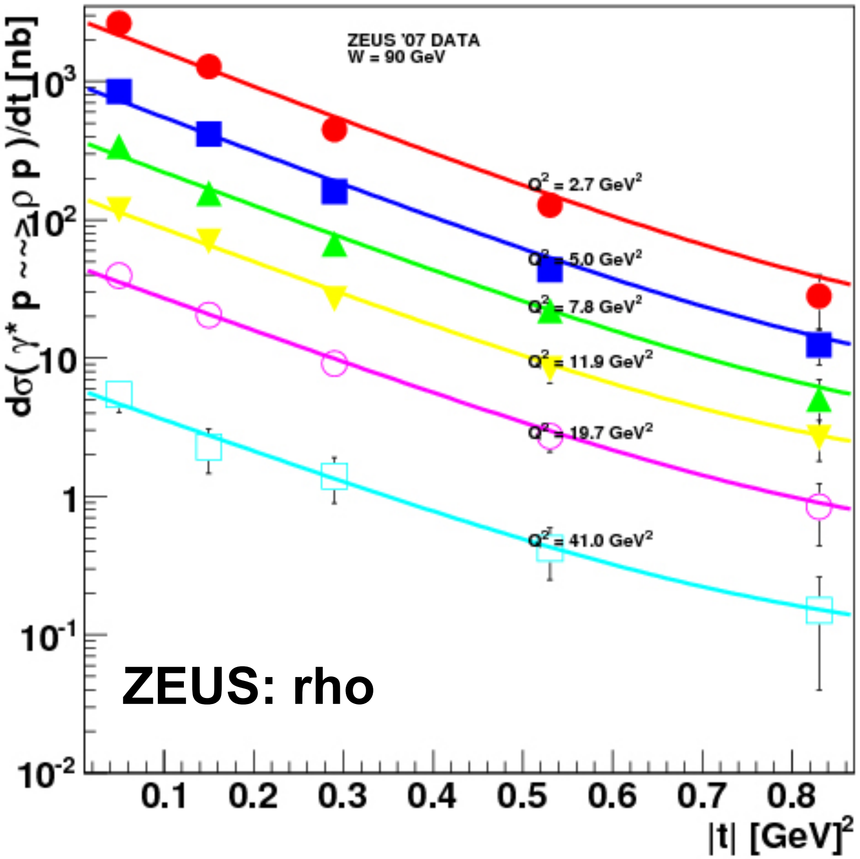


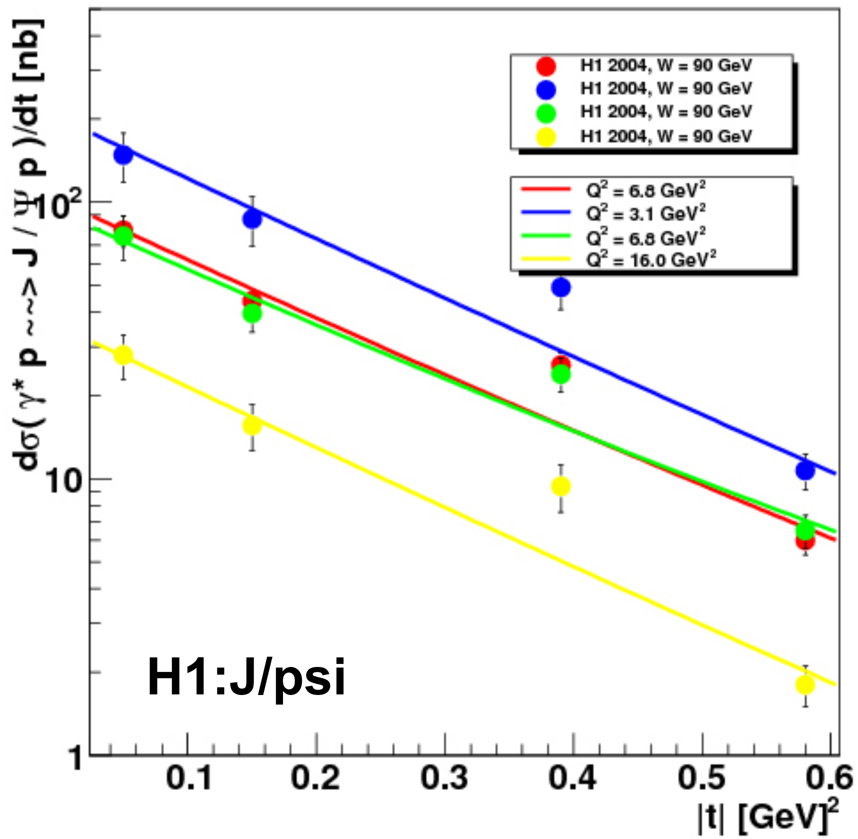


The model provides a good description of the $\sigma(Q^2)$ for J/ψ but it still fails to describe ρ^0 at high Q^2

VM (two Pomerons contribution)

Model compared to dσ/dt with all param. fixed and only norm. free

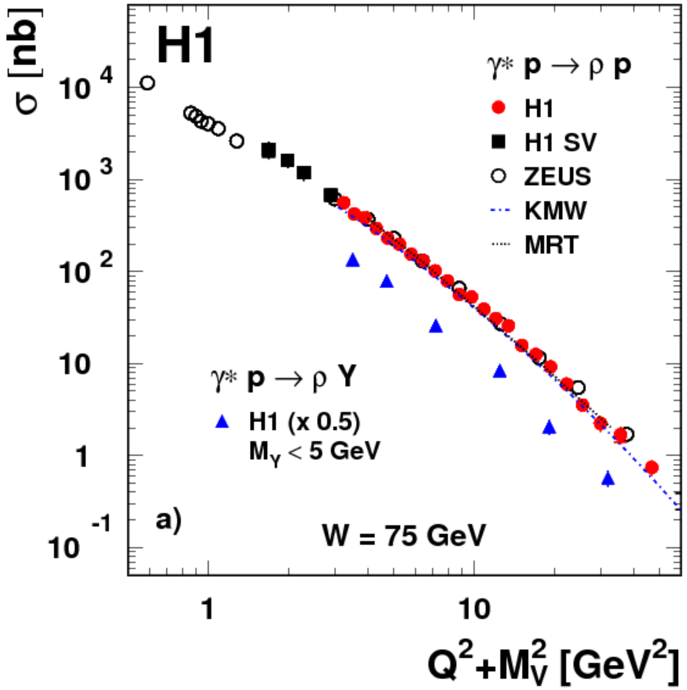


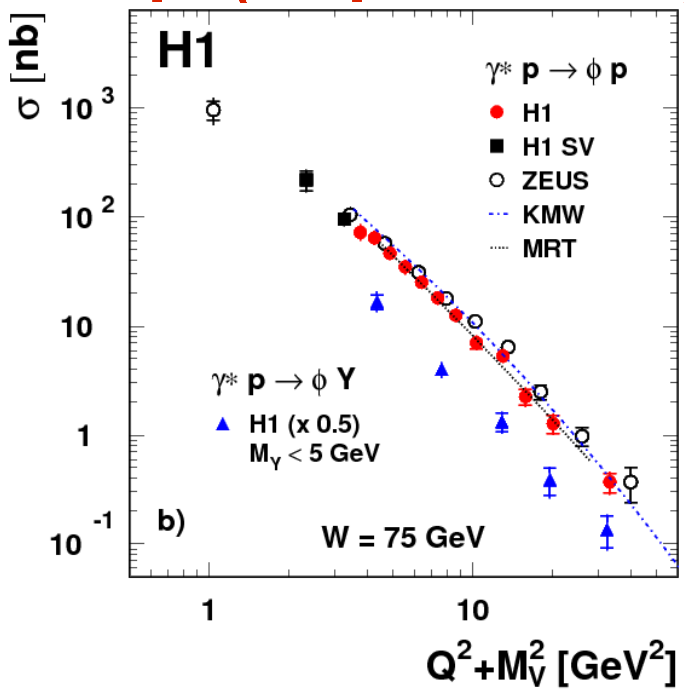


The model reproduces the dσ/dt, especially at high Q^2

Q^2-dependence

ρ^0 ($M^2\rho$ = 0.5 GeV^2) φ^0 ($M^2\varphi$ = 1 GeV^2)





$$\sigma \propto \left(Q^2 + M^2\right)^{-n}$$

Fit to whole Q^2 range gives bad χ^2/df

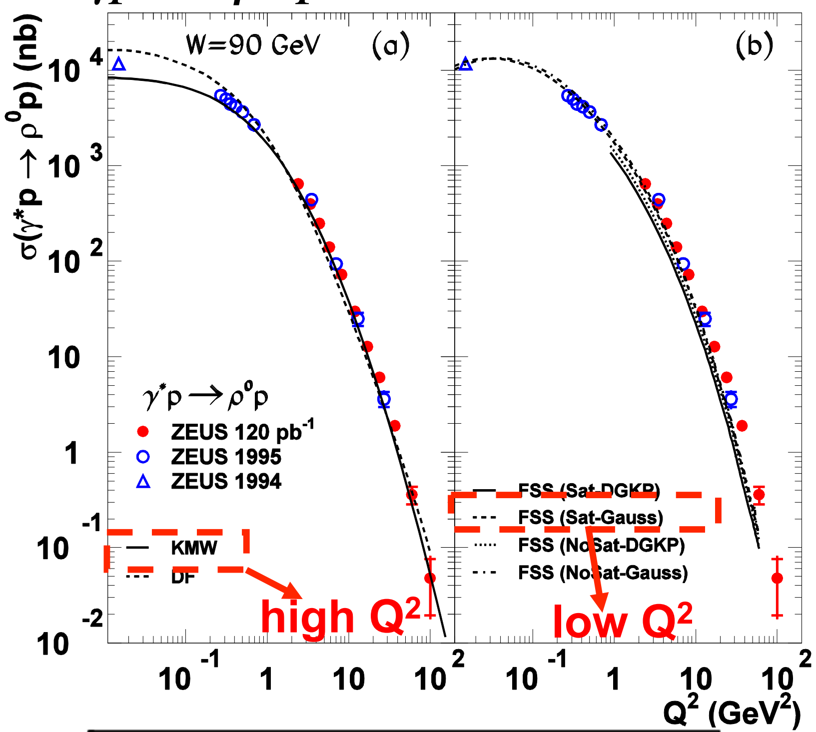
Good H1/ZEUS agreement

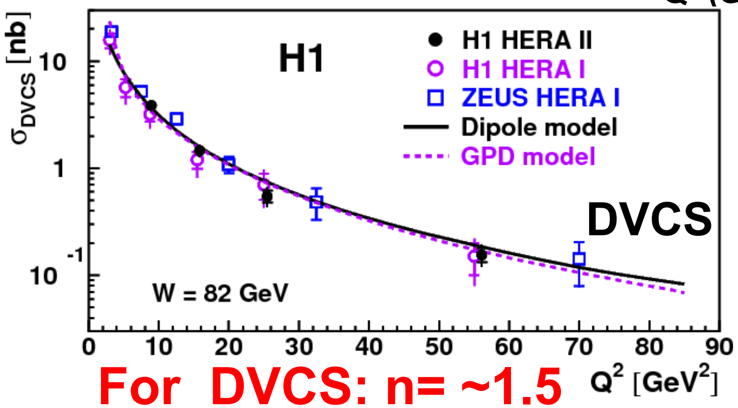
DESY-09-093

- $Q^2 \geq 0$ GeV^2, n≈2.00±0.01, $\chi^2/ndf \sim 10$ (n ≠ const)
- $Q^2 \geq 10$ GeV^2, n≈2.50±0.02, $\chi^2/ndf \sim 1.5$

Q^2-dependence

$\gamma p \to \rho^0 p$ ZEUS



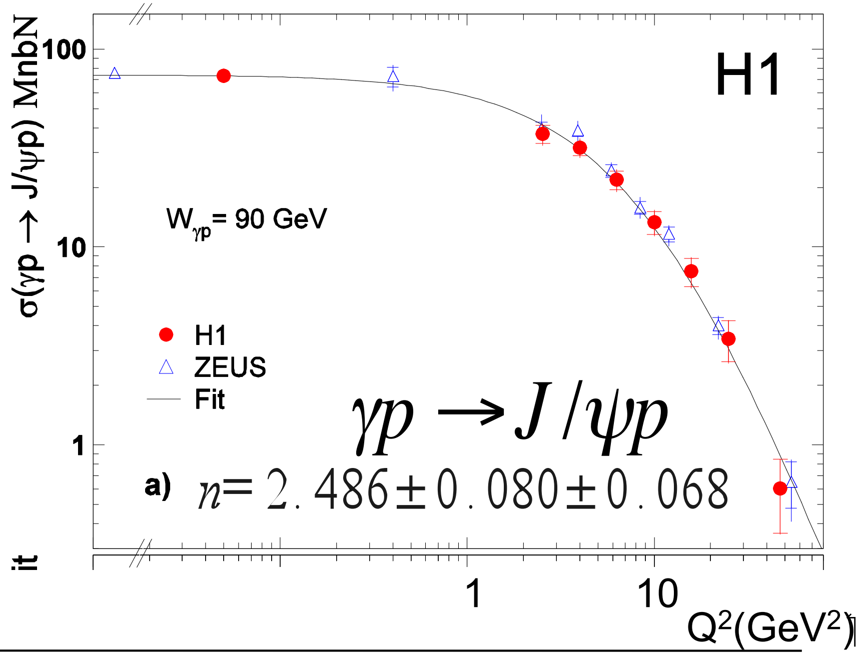


For DVCS: n= ~1.5

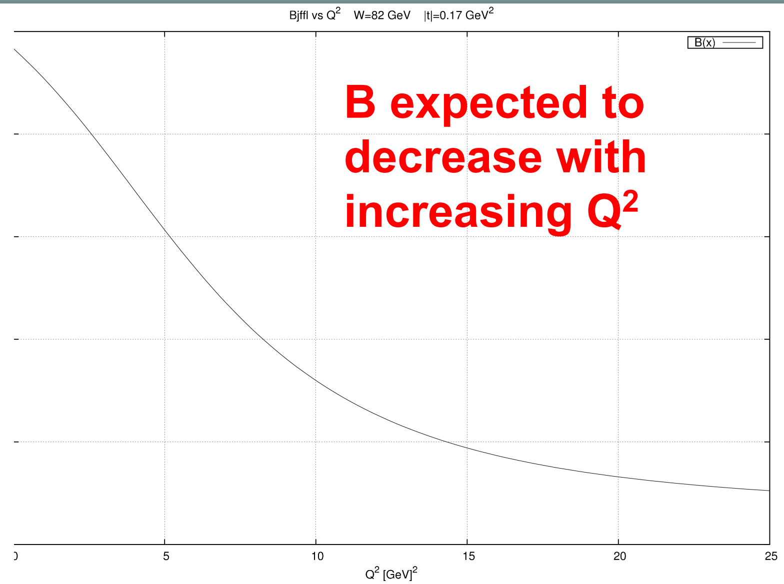
$$\sigma \propto \left(Q^2 + M^2\right)^{-n}$$

Fit to whole Q^2 range gives bad χ^2/df (~70)

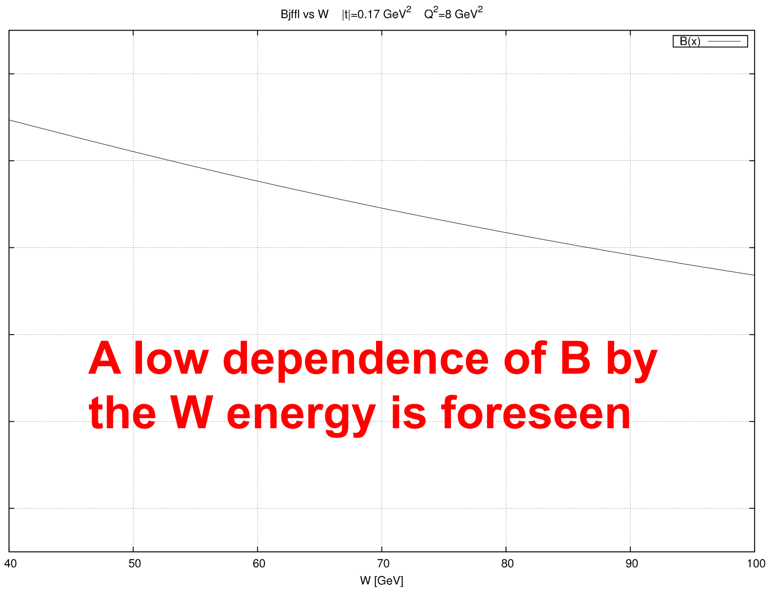
***n* increasing with *Q^2* appears to be favored**

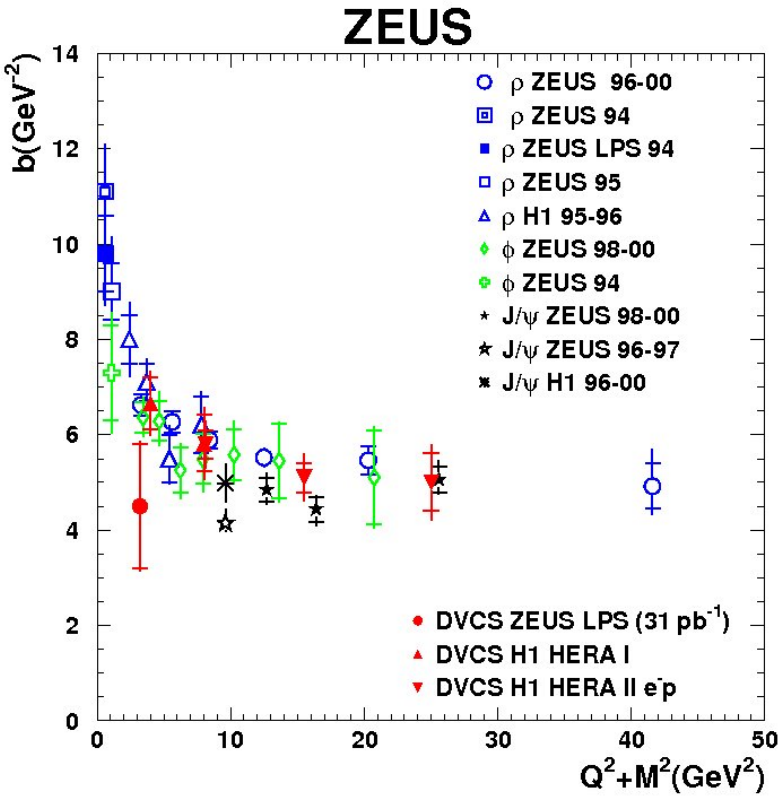


B dependence



$$B = \frac{d}{dt}\ln\left(\frac{d\sigma}{dt}\right)$$

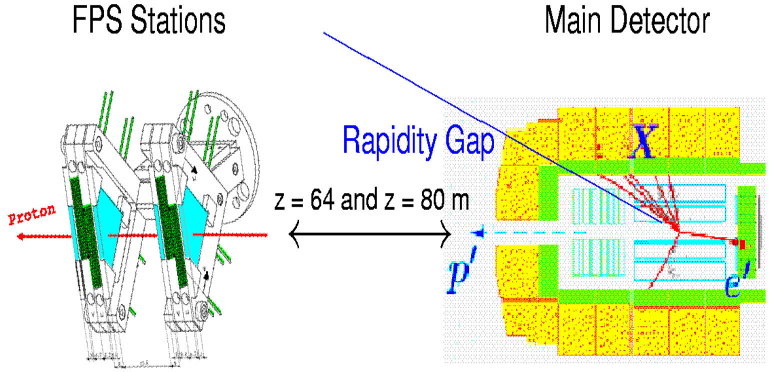


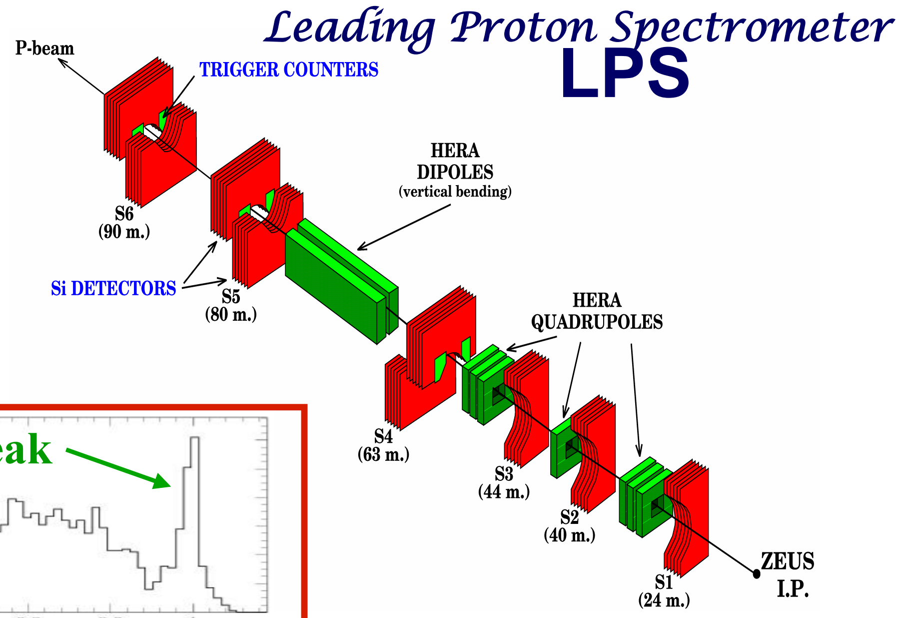


Summary & outlook

- **A lot of experience carried over from HERA**
  - **EIC forward program can sensibly improve HERA**
- **DVCS is the best tool for GPDs investigation**
- **A logarithmic Pomeron trajectory can reproduce DVCS data.**
- **A Regge-type model describes both DVCS and VMP processes**
  - **Next step will be to use our model for GPD calculations: real and imaginary parts of the DVCS amplitude explicitly contained in the model**

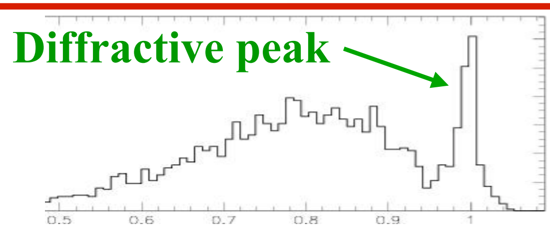
Back up





p tag method

- o Measurement of *t*
- o Free of p-diss background
- o Higher M_X range
- o Lower acceptance

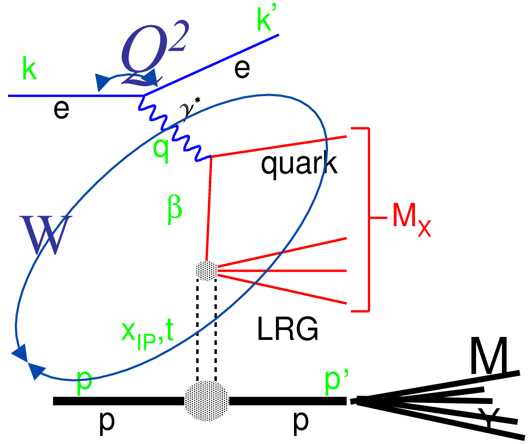


$$x_L = \frac{p'_z}{p_z} \approx 1 - x_{IP}$$

NB: if scattered proton not detected, background from proton dissociative events

Large Rapidiy Gap method

- ❑*X* system and e' measured
- ❑System *Y* not measured, some theoretical and experimental uncertanties
- ❑Integrate over $t<1GeV^2$ and $M_Y<1.6$ *GeV*
- ❑High acceptance



DVCS @ ZEUS – Selection criteria

$L = 61.14\ pb^{-1}$

- **$99e^{+}$-00 ZEUS data**
- **Two Sinistra candidates**
- **First candidate in RCAL**
- **Second candidate in RCAL or in BCAL**
- **1 or 0 tracks**
- **rear box cuts**
- **Elasticity cut**
- **Energy in FCAL < 1 GeV and in FPC < 1GeV**
- **$-100 < Zvtx < 50$ cm**

Monte Carlos:

GenDVCS	(400k DVCS events)
Grape-Compton	(400k el. BH events 400k inel. BH events)
Grape-dilepton	(150k dilepton events 150k inel. dilep. events)
DiffVM $J/\Psi \longrightarrow e^{+}e^{+}$	

JHEP05(2009)108

Kinematic region:

$1.5 < Q^2 < 100\ GeV^2$

$40 < W < 170$ GeV

Energies & angle:

$E_1 > 10$ GeV

$E_2 > 2$ GeV

$\theta_2 < 2.85$

PLB 573 (2003) 46-62

Kinematic region:

$5 < Q^2 < 100\ GeV^2$

$40 < W < 140$ GeV

Energies & angle:

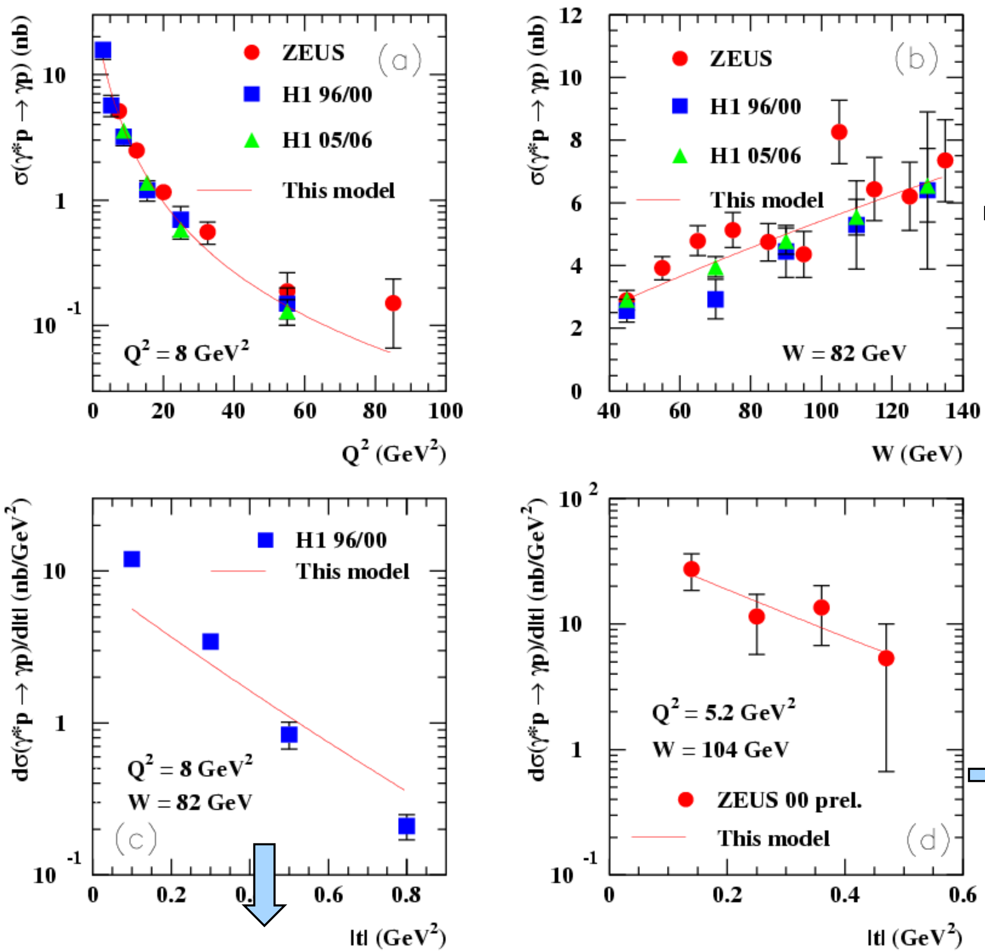
$E_1 > 15$ GeV

$E_2 > 2.5$ GeV

$\theta_2 < 2.75$

A single "effective" Pomeron in DVCS

DVCS data collected at HERA



$$\frac{d\sigma}{dt}\left(s,t,Q^2\right) = \frac{\pi}{s^2}\left|A\left(s,t,Q^2\right)\right|^2$$

Fit was performed on $\sigma(Q^2)$ and $\sigma(W)$

$\alpha(0) \sim 1.2 \approx \alpha(0)$ hard

$\alpha' \sim 0.25 \approx \alpha'$ pp coll.

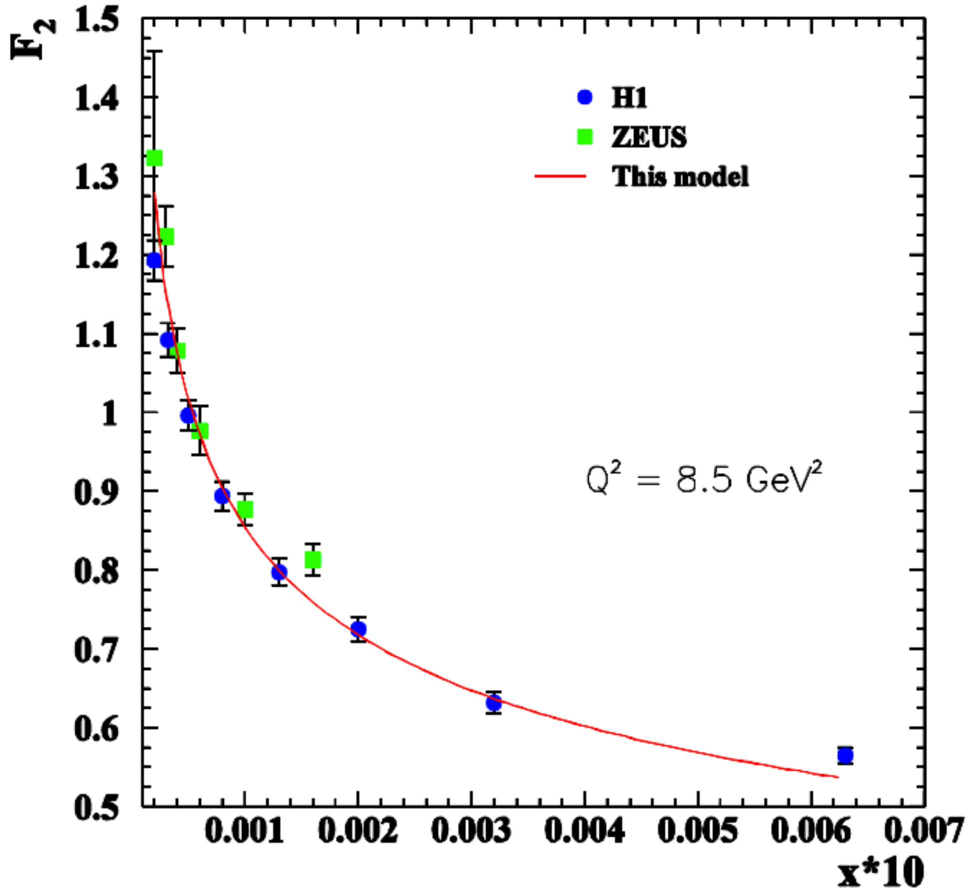
As for hh interactions

Model compared to $d\sigma/dt$ with all param. fixed and only norm. free

Disagreement with H1 measurement

F_2 stucture function

Comparison between HERA data and the model for
***$F_2(s,Q^2)$* DIS structure function**

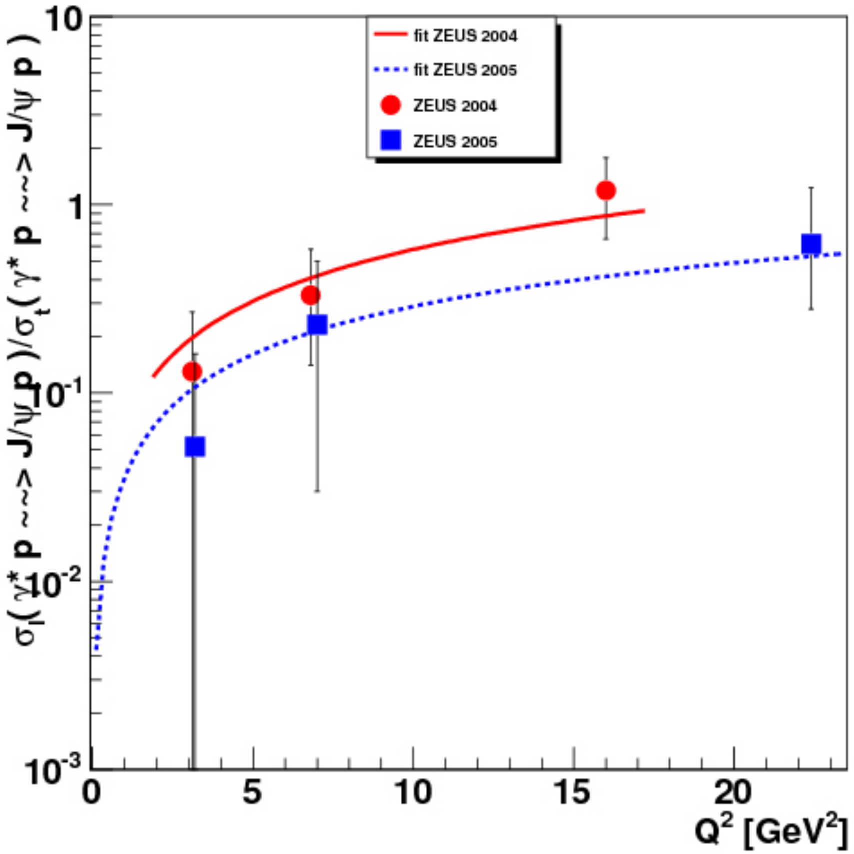


$$F_2\left(s,Q^2\right) \approx \frac{(1-x)Q^2}{\pi\alpha_e} \Im A(s,Q^2)/s$$

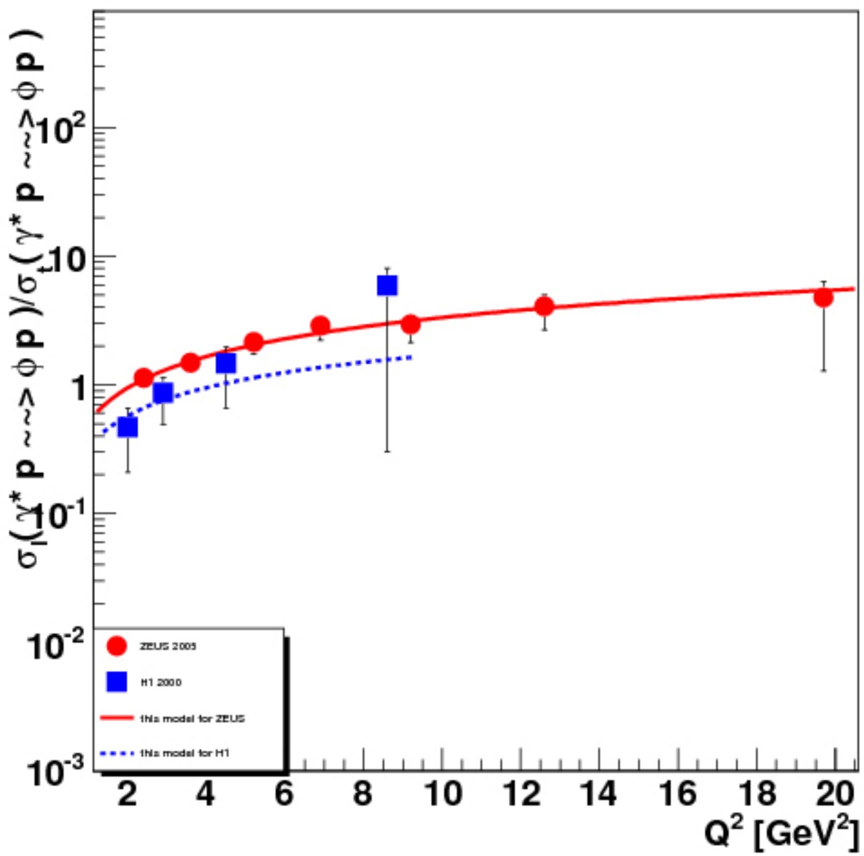
All parameter fixed like in our model

Really good agreement!

The model reproduces experimental data at small *x* and moderate Q^2



fit ZEUS 2004
fit ZEUS 2005
ZEUS 2004
ZEUS 2005
σ_l(γ* p ~~> J/ψ p)/σ_t(γ* p ~~> J/ψ p)
Q² [GeV²]



ZEUS 2005
H1 2000
this model for ZEUS
this model for H1
σ_l(γ* p ~~> φ p)/σ_t(γ* p ~~> φ p)
Q² [GeV²]